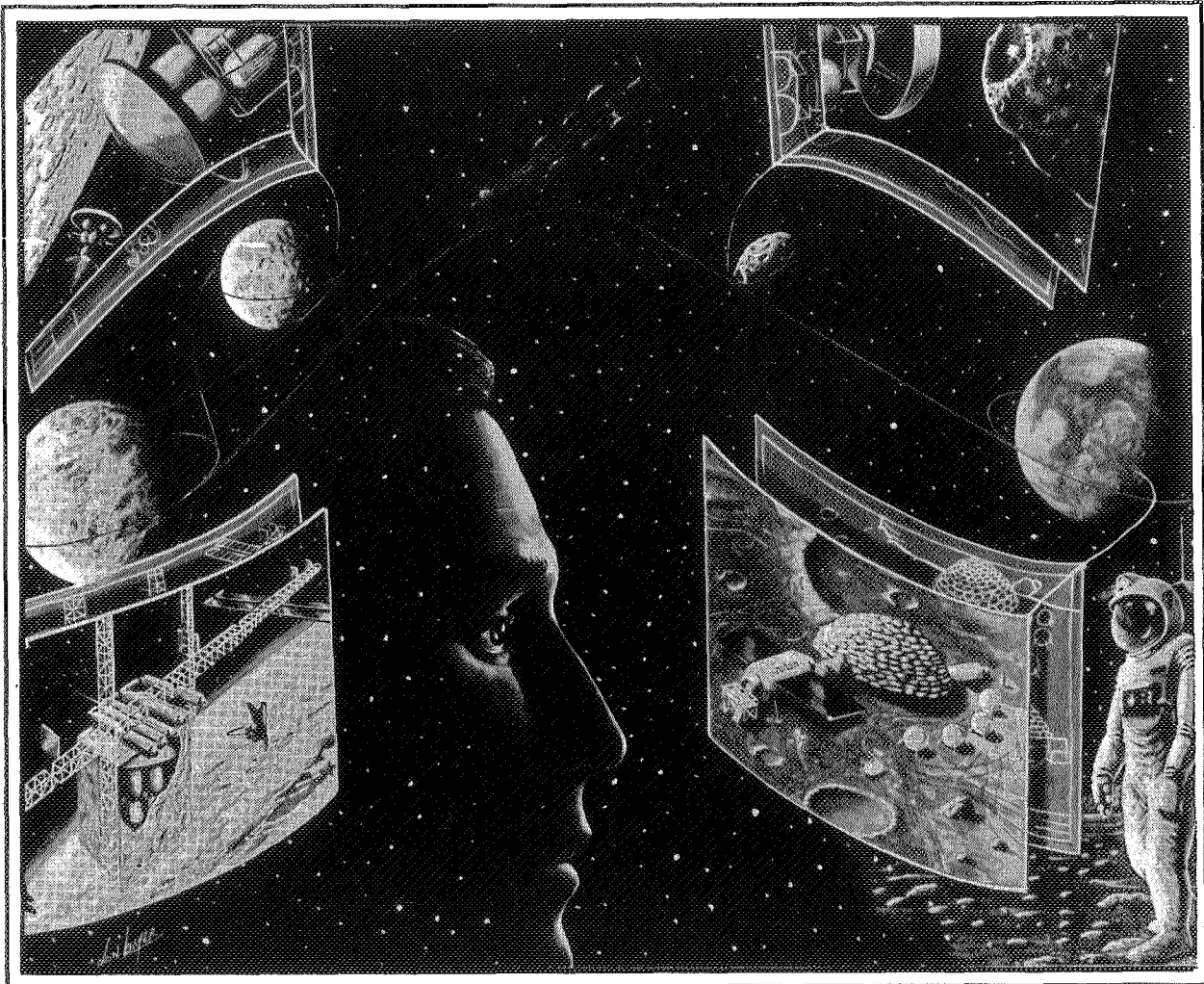


OFFICE OF EXPLORATION  
**Exploration Studies Technical Report**  
FY 1988 STATUS



**Volume I: Technical Summary**

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**December 1988**

*This publication is one of four documents describing work performed in fiscal year 1988 under the auspices of the newly formed Office of Exploration. The first in the series, titled, "Beyond Earth's Boundaries . . . Human Exploration of the Solar System in the 21st Century" provides an overall programmatic view of the goals, opportunities, and challenges of achieving a national goal for human exploration. The technical details and analyses are described in a three-volume set titled: "Office of Exploration: Exploration Studies Technical Report (FY 1988 Status)." Volume I is a Technical Summary; Volume II is the Study Approach and Results; and Volume III is a collection of trade study results, indepth systems assessments, and workshop reports which describe aspects of FY 1988 analyses in more depth.*

**NASA Technical Memorandum 4075**

**Office of Exploration  
Exploration Studies Technical Report  
FY 1988 Status**

**Volume I - Technical Summary**

**December 1988**



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# Preface

The Office of Exploration (OEXP) was established in June 1987 to provide recommendations and viable alternatives for an early 1990s national decision on a focused program of human exploration of the solar system, particularly of the Moon and Mars. The OEXP is also responsible for steering Agency investments on a practical, year-by-year basis toward providing feasible, defined choices in the early 1990s. With management centralized at NASA Headquarters, the OEXP leads a NASA-wide team consisting of all the major program offices and field center organizations that are specifically dedicated to this effort.

To accomplish OEXP objectives, a study process was developed that begins with the yearly articulation by OEXP of guidelines and ground rules for human exploration studies. This activity serves to define a framework of initial concepts within which alternative strategies can be formulated and explored. The methodology used for implementing various strategic approaches, such as expeditions, science outposts, and evolution, is to identify reference missions to be examined as "case studies."

Once case studies have been identified by the OEXP, the Mission Analysis and System Engineering (MASE) function at JSC coordinates development of detailed case study descriptions and study initialization requirements and data. Detailed technical analyses at the element/systems level are then performed by designated field center Integration Agents (IAs) and Special Assessment Agents (SAAs). There are three IAs, each IA covering one of three principal areas of study responsibility: orbital node systems, space transfer vehicle systems, and planetary surface systems.

SAAs, through direct assignment from OEXP and on their own initiative, conduct independent assessments at an in-depth systems analysis and trades level. These studies are usually highly analytical in nature and focus on mission or vehicle systems having a high potential for advanced technology exploration mission objectives. Respective IA and SAA study activities are supported as required by technical experts from virtually all of the NASA field centers.

Study progress for each case study is reported at periodic program reviews. These reviews generally include all study agents and support center representatives and

often include representatives from each of the NASA Headquarters codes whose program support would be required in the execution of one or more of the case studies. Each of the affected NASA program offices submits hypothetical case study implementation plans which include analyses of each case study's effect on the office's strategic program plans and schedules.

The yearly outcome of this Agency-wide team effort is an annual report which progressively matures in its degree of technical and programmatic legitimacy. This report serves to document specific conclusions about the year's study efforts and provides valuable source material for planning subsequent study year activities.

In conjunction with case study definition and development of exploration cases, a parallel effort is to consider what these missions mean in terms of advancing scientific knowledge. The work performed in FY 1988 has been too preliminary to constitute a science strategy but has looked to incorporate some ideas on scientific objectives into the engineering analysis. In the future, the scientific rationale for human exploration missions will be more comprehensively developed.

This report describes the process that has been formulated to conduct exploration studies and discusses those missions that have formed the backdrop for FY 1988 work. A "case study" approach has been developed and used, with the intention not of selecting one case in preference to the others but rather of isolating and identifying potential requirements and sensitivities that influence case study complexity, feasibility, and benefits.

Four case studies were developed during FY 1988: (1) Human Expedition to Phobos, (2) Human Expeditions to Mars, (3) Lunar Observatory, and (4) Lunar Outpost to Early Mars Evolution. Selected to encompass a broad spectrum of objectives, capabilities, and requirements, these cases also cover a variety of potential destinations, emphases for exploration, crew size, and activities on planetary surfaces.

In the course of the detailed definition and assessment of the case studies, many insights have been gained, regarding both specific case studies and human exploration missions in general. These topics, as well as other results of the FY 1988 study activity, are summarized in this volume.

# Exploration Strategy

## Definition

The Presidential Directive on National Space Policy, signed into effect on January 5, 1988, clearly establishes a positive thrust to launch the United States toward visionary accomplishments in space. Of particular significance is the directive that sets the long-range goal "to expand human presence and activity beyond Earth orbit into the solar system." For the first time in the history of the space program, the U.S. has an explicit national policy mandate that challenges us to move permanent human activity beyond Earth's boundaries.

Determining ways in which the civilian space program can meet this goal is the responsibility of the Office of Exploration, supported by a NASA-wide effort. Although national policy directs NASA to expand human exploration, no specific guidelines exist regarding the pathways, timing, or concentration of purpose. To formulate a logical plan to achieve the goal of human exploration, it is important to first identify and comprehend the rich array of possibilities. Developing a philosophical viewpoint that articulates the underlying motivation for such a program forms a template for the more practical aspects of activities to meet exploration objectives.

To begin to define this motivation, seven major "themes" — national pride and international prestige, advancement of scientific knowledge, technology catalyst, economic benefits, space enterprise, international cooperation, and education and excellence — that have most often been associated with the space program were reviewed. An awareness of the ways in which meeting the objectives embodied in these themes can be enhanced by human intellect, energy, and participation helps to guide the selection of potential pathways for human exploration.

Each proposed human exploration scenario must be examined in terms of how it satisfies the themes or rationales for which such missions are intended and undertaken. These concepts must be understood in light of the fundamental values held by our society, in order to elicit and sustain widespread support for our long-range goals.

To organize and systematically examine a full range of options for human exploration and development of the Moon and Mars, three strategies were identified for study in FY 1988. Each strategy presents particular opportunities for meeting defined exploration themes and objectives.

The first strategy addresses human **expeditions**, emphasizing a significant, visible, successful effort to establish the first human presence on another planetary body. The expeditionary pathway would lead to exploration without the burden and overhead associated with permanent structures and facilities. This pathway has been explored for missions to Mars and to its moons.

Establishing a **science outpost**, the second strategy, emphasizes advancing scientific knowledge and gaining operational experience by building and operating an extraterrestrial outpost as a permanent observatory. This pathway has been explored for a mission to the Moon.

The third strategy, **evolutionary expansion**, would sustain a methodical, step-by-step program to open the inner solar system for exploration, space science research, in-situ resource development, and ultimately, permanent human presence. This strategy would begin with an outpost on the Moon and progress to a similar base of operations on Mars, establishing systems and infrastructure for further expansion, which is yet to be defined.

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# Exploration Case Studies

## Case Study Approach

Exploration strategies are developed through a "case study" process. The purpose behind developing reference case studies is to define a set of strategies that respond to different objectives or modes of implementation, so that a reasonable range of options can be understood. The number of potential case studies is very large, but only a few can be studied in depth. Additional cases can be constructed by rearranging elements or by extending the reference cases through trade studies that examine the effects of varying assumptions.

The case study process is iterative in nature among and within three distinct phases (see Figure 1). The first phase addresses conceptual mission and system architectures. As part of this effort, mission and system requirements are defined to meet the exploration goals and objectives and user requirements. The mission and system requirements specify functional and performance parameters for elements defined by this study, identify environments in which elements must operate, and identify element design and operational constraints.

The second phase of the case study process addresses conceptual element definitions, which are responsive to

the mission and system concepts developed in phase one. Three areas were determined to be significant case study elements: space transportation systems, orbital nodes, and planetary surface systems. All are, in general, programmatically independent and can be addressed initially as functionally independent. The conceptual definition of these elements includes scaling data to support the synthesis in the next phase.

The third phase is a synthesis of the element concepts back into an integrated mission and system. The results establish a preliminary system concept and a reference configuration that is used to refine the study through several iterations. Where unique science and/or technology needs were identified, such as the possible implementation of nuclear spacecraft propulsion, special studies or assessments were made to identify strategies to accommodate those needs. A complementary set of broad trade studies, which are not case study specific, but which identify and assess key sensitivities, is run in parallel with these three phases. The refined case studies, associated requirements, and determined benefits become the knowledge base of exploration pathway sensitivities, which in turn is used to define the exploration initiative

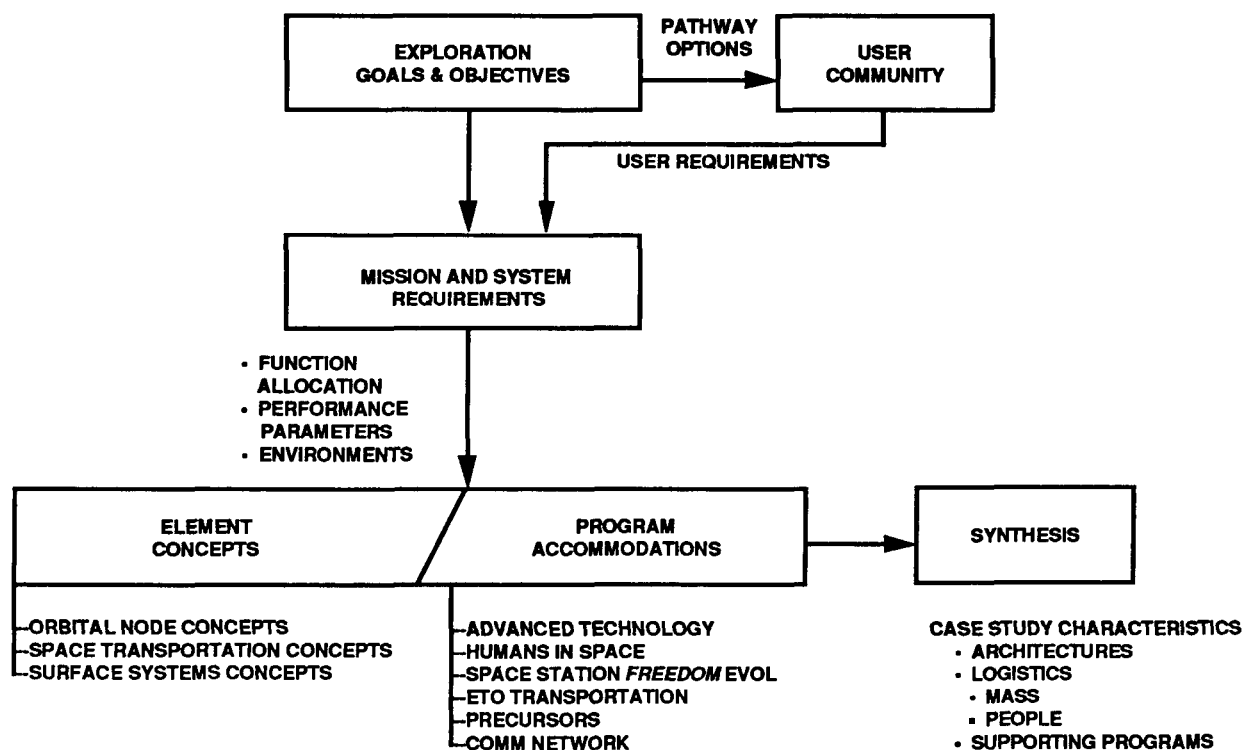


Figure 1.- Case study methodology

options, benefits, and risks.

A case study may be viewed as a combination of building blocks: interplanetary trajectory, launch vehicles, transportation node, space transfer vehicles, and surface systems. The combination of specific element options characterizes the case study in terms of technology required, schedule, capacity, complexity, and cost.

The trajectory may be considered the most basic component. For trips to the Moon, the path is relatively straightforward. The spacecraft is not required to leave Earth's sphere of influence, it only takes three days to get there (or back), and launch opportunities occur quite frequently. Interplanetary transfers, specifically from Earth to Mars, are more complicated. For a given class of trajectory, an opportunity to launch to Mars occurs only once every 26 months, and mission performance can vary widely, depending on launch date and round-trip travel time.

Three types of round-trip trajectories are employed in Mars exploration case study design: opposition, sprint, and conjunction. The opposition class is characterized by round-trip times of approximately 600 days, and provides the important ability for a Mars-flyby abort. The sprint, a subset of the opposition, also has the capability for an abort maneuver, and is characterized by round-trip times of approximately 400 days, with associated high energy requirements. The conjunction-class is a much longer round trip, approximately 1,000 days, but it has minimum energy requirements. For many human exploration missions, a "split/sprint" technique is employed to minimize trip time. The cargo is launched on a minimum-energy trajectory (identical to the outbound leg of a conjunction-class round trip), whereas the crew carrier makes use of a high-energy sprint trajectory. A typical split/sprint trajectory profile is illustrated in Figure 2. In some launch years, a swingby of Venus may be effected to use its gravity to assist the piloted spacecraft, thereby reducing launch requirements.

Another important factor is Earth-to-orbit transportation, viewed in terms of both the amount of mass that must be lifted from Earth's surface and the number and type of launch vehicles needed. Launch vehicles that are assumed for use in case study development are the Space Shuttle, a heavy-lift launch vehicle, and other proposed reusable and expendable vehicles.

An element that enables or enhances most of the cases is an orbiting node for the assembly and servicing of vehicles, transfer of crew, and replenishment of propellant. Space Station Freedom and its evolutionary elements are used in some case study designs, but other alternatives are being examined as well.

Space vehicles are dependent on the choice of target and

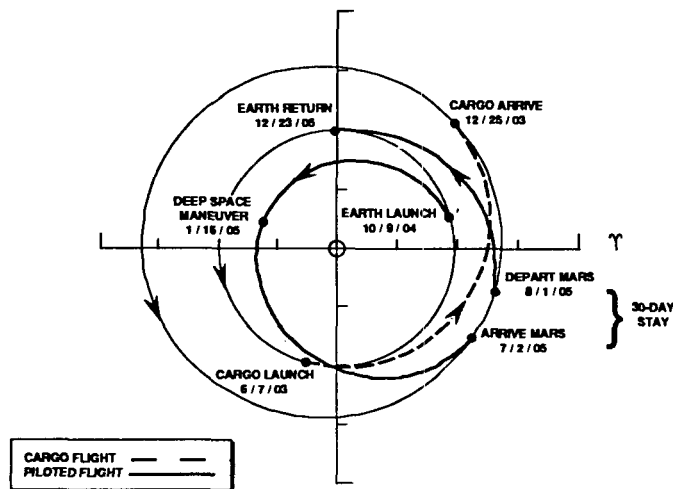


Figure 2.- Representative split/sprint trajectory profile

the plan for post-landing activities. Vehicles must be designed, for example, to transfer the crew and its cargo of supplies and equipment from a transportation node to the ultimate destination and back again. Other vehicles, to descend to and traverse planetary surfaces, must also be developed.

Surface systems are also dependent on the choice of target and the plan for post-landing activities. Living quarters, for example, may be required for the crew on the surface. Vehicles to traverse and explore extraterrestrial surfaces must also be developed.

The four case studies described below are intended to serve as a backdrop for identifying and examining the larger issues of human exploration. No order of priority is implied, nor should it be assumed that any one case will represent the final goal. In the coming years, the case studies will be refined, new ones will be added, and the implementation options may be narrowed. The underlying goal of this effort is to isolate approaches, options, and requirements, to enable an informed choice in the future.

#### Human Expedition to Phobos (Case Study 1)

A primary objective of this mission is the establishment of early leadership in the human exploration of the solar system. To that end, baseline vehicles are designed for minimum dependence on advanced technology, and human presence is extended only to Mars orbit and the surface of Phobos. In this case study, the first human beings will arrive at the Martian moon Phobos to explore, conduct resource surveys, and establish a science station. Other key objectives are to conduct enhanced robotic exploration of Mars itself from Mars orbit, using rovers,

penetrators, balloons, and sample collectors, and to return samples of Mars and Phobos to Earth for detailed analysis. The expedition to Phobos combines human exploration objectives with those of previously studied Mars Rover/Sample Return (robotic) missions, but allows different approaches to the exploration of Mars because of the capability for nearly real-time teleoperation of robotic systems from the vicinity of Mars.

### Mission Description

The mission scenario, illustrated in Figures 3 and 4, employs a "split/sprint" trajectory: a cargo vehicle carrying the Phobos and Deimos exploration equipment, Mars rovers, and the crew's return propellant will be launched via an expendable escape stage on a minimum-energy trajectory in February 2001. Upon arrival, this vehicle will be placed in Mars orbit to await the piloted flight. In August 2002, approximately 18 months after the first launch, a second vehicle carrying a crew of four will be launched via an expendable escape stage on a high-energy sprint-class trajectory, which requires about 9 months to reach Phobos.

Upon arrival in Mars orbit, the piloted vehicle will rendezvous with the cargo vehicle. Two crew members will transfer to a Phobos Excursion Vehicle and depart for a

20-day exploration of the Martian moon. During that time, the crew on Phobos will make observations, conduct experiments, and gather samples during a total of 24 hours of extravehicular activity. The two crew members who remain in the orbiting vehicle will teleoperate, or remotely control, rovers which will gather samples from the surface of Mars. After spending a total of 30 days in the Martian system, the crew will return directly to Earth, a 4-month trip. The total length of the mission is 440 days.

### Results

The Phobos mission is potentially the earliest to arrive of the four case studies. A number of factors unique to this mission contribute to this capability. First of all, it may be possible for the expedition to Phobos to be completed without an assembly node in low-Earth orbit (LEO). However, two operations must take place in LEO: mating of elements and payloads, and transfer of propellant (either fluid transfer or exchange of tanks) between Earth-to-orbit delivery vehicles and the vehicles carrying cargo and crew to Mars. In Mars orbit, a stage exchange or propellant transfer is effected between cargo and piloted vehicles. Therefore, the systems and techniques to robotically join elements and payloads in low-Earth orbit must be developed, in addition to those for cryogenic propellant storage and transfer in Earth and Mars orbit.

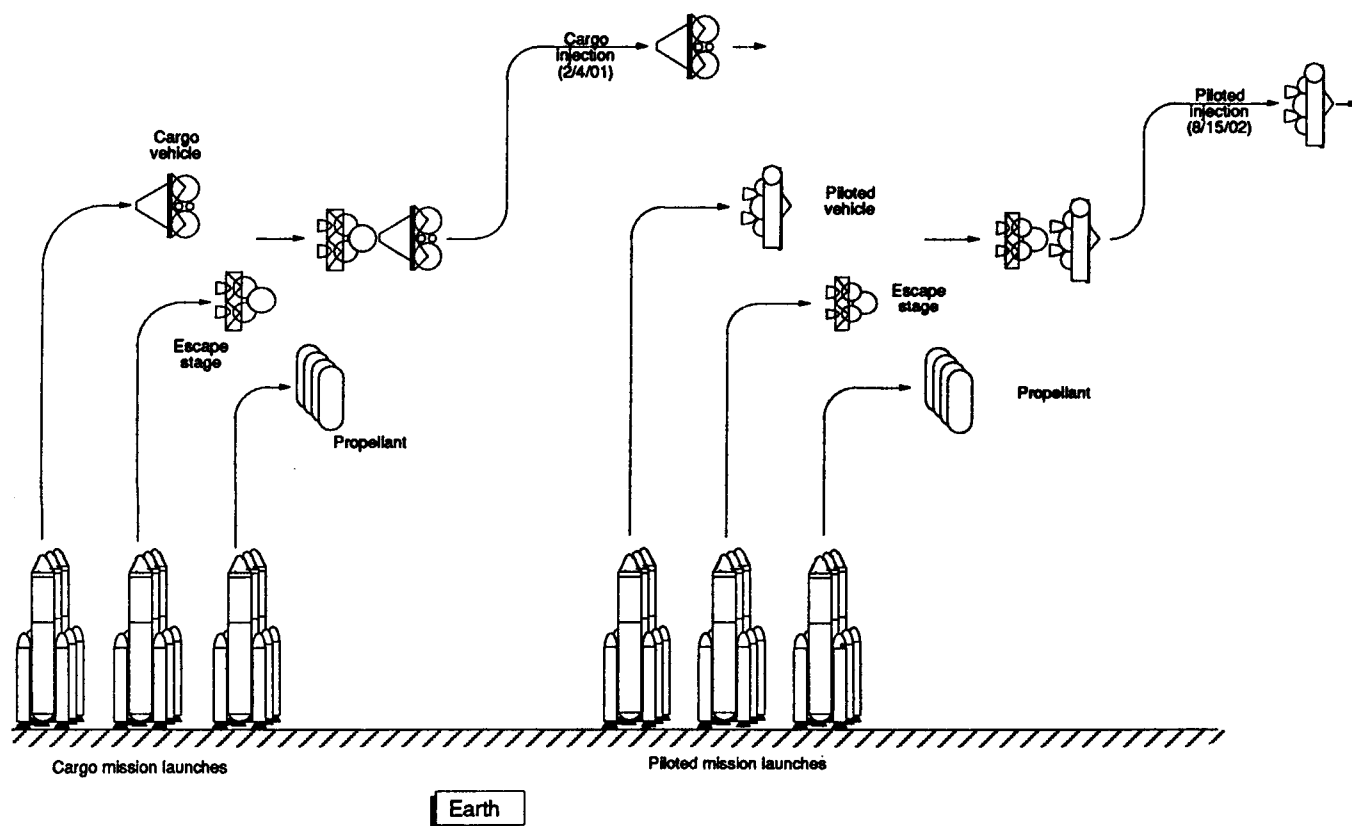


Figure 3.- Human expedition to Phobos—Earth-orbital operations

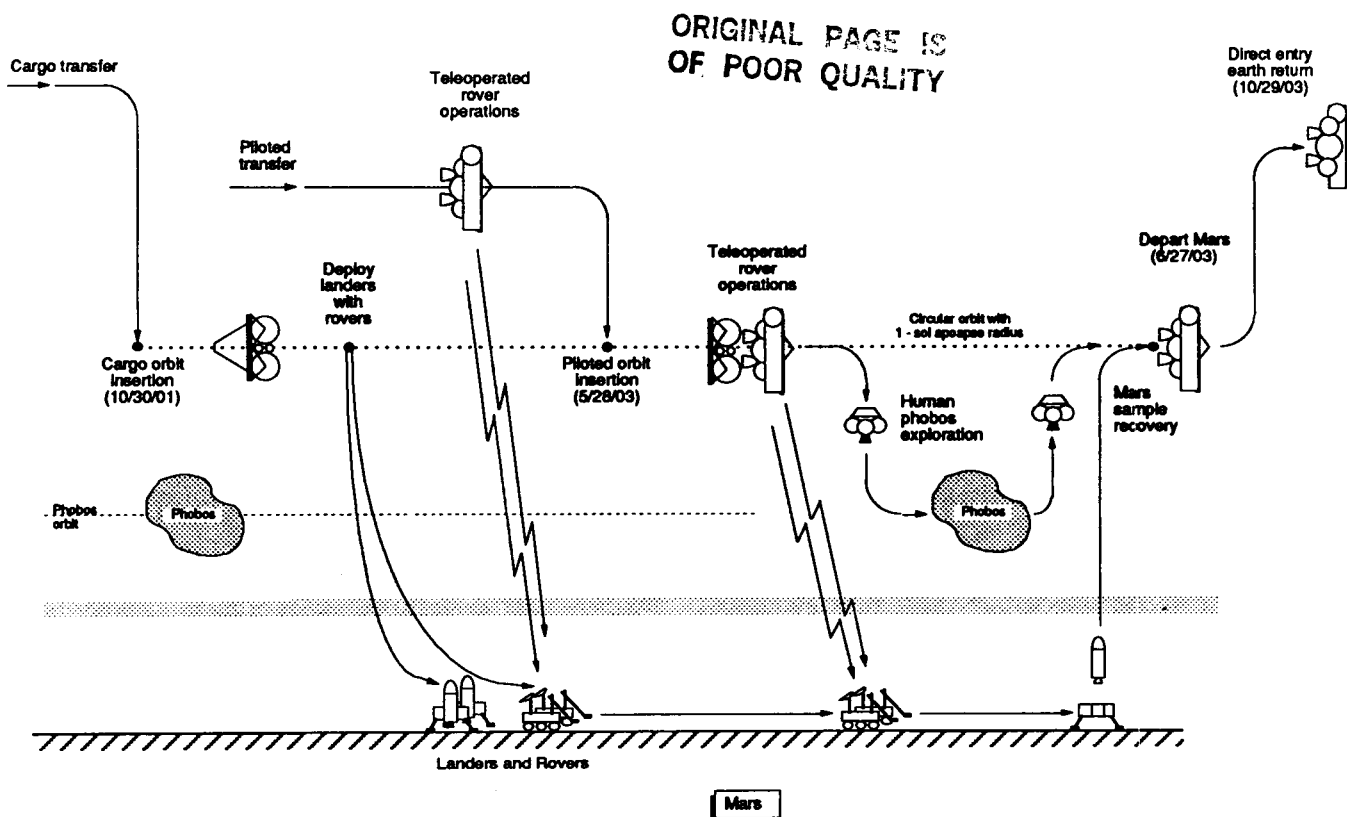


Figure 4.- Human expedition to Phobos—Mars/Phobos orbital operations

The fact that the crew does not land on the surface of Mars simplifies both the scenario and the requirements for the mission, and substantially increases the likelihood of achieving the principal goal of being first. With the exception of the rover systems, no other Mars surface landing systems are needed, either for equipment or for crew. This greatly reduces the initial mass to LEO requirement, as well as the time required for exploration program development and for the supporting technology and precursor programs.

The Phobos mission could be an excellent precursor to a piloted Mars landing mission. The robotic exploration of Mars will provide improved knowledge of the Martian environment. The Phobos mission will provide a unique opportunity to perform a systems checkout and verification of flight hardware and environment without the increased difficulty of a Mars landing. Given the ground rules and assumptions for the FY 1988 studies, these considerations allow a "Mars-class" mission to be accomplished four and a half years before the first Mars landing of the Mars expedition case.

The Phobos Expedition was baselined for the FY 1988 studies to assume propulsive capture into orbit about Mars. Subsequent analysis showed that such large masses in LEO were required that it was unlikely that this expedition could be flown without at least some infra-

structure in LEO. This is because the mass requirement in LEO results in 20 to 30 ETO launches and the resulting integration in orbit. As will be discussed later in this report, aerocapture upon Mars arrival was found to offer such a significant improvement in IMLEO that the results presented in this report assume the aerocapture option for the Phobos Expedition, unless otherwise noted.

### Human Expeditions to Mars (Case Study 2)

A primary objective of this three-mission set is to send the first human explorers to the Martian surface in order to capture early leadership in the piloted exploration of the solar system. Once there, the crew would conduct local geological reconnaissance, emplace long-lived geophysical instruments, and collect samples for return to Earth. An additional key objective is to conduct ancillary exploration of the Martian moons, Phobos and Deimos.

### Mission Description

The transportation strategy employed for each of the three missions will be a split/sprint trajectory; an example of the mission scenario is provided in Figures 5 and 6. For the first expedition, a cargo transport carrying the landing vehicle (including Mars surface habitat and exploration equipment and the ascent vehicle), and the Earth-return propellant will be launched via an expend-

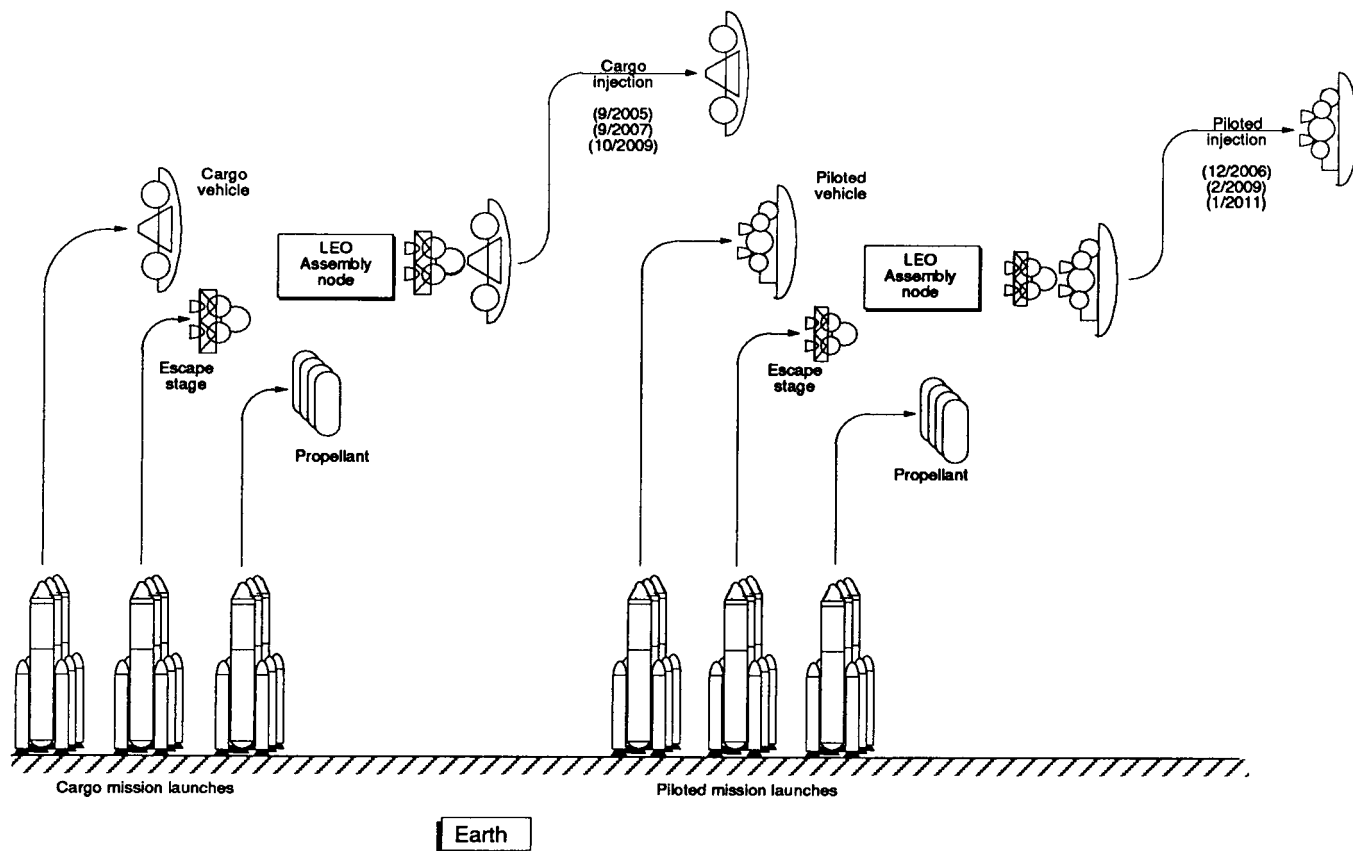


Figure 5.- Human expeditions to Mars—Earth orbital operations

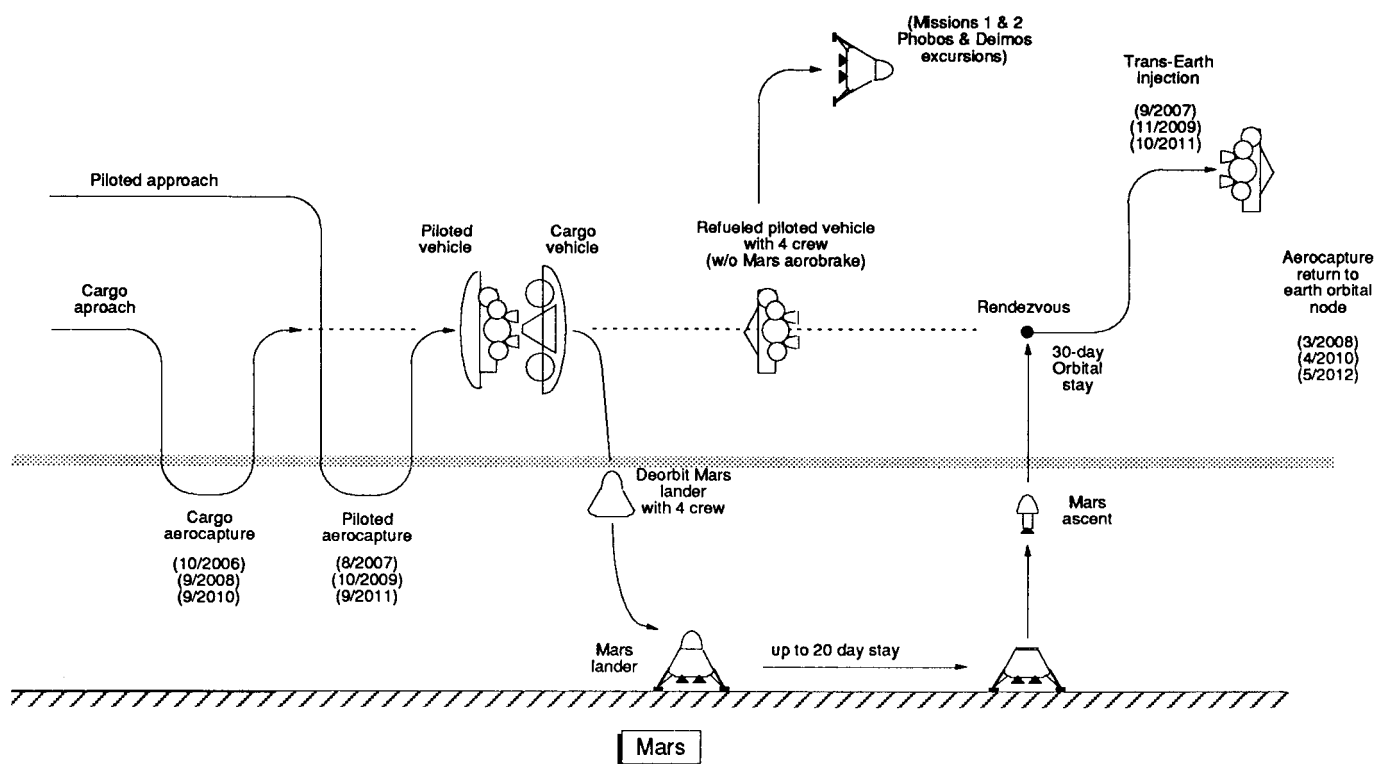


Figure 6.- Human expeditions to Mars—Mars orbital/surface operations

able escape stage on a minimum-energy trajectory in September 2005. Upon arrival at Mars, this vehicle will be placed in Mars orbit to await the piloted flight. In December 2006, approximately 15 months after the first launch, a vehicle carrying eight crew members will be launched via an expendable escape stage on a high-energy, sprint-class trajectory.

Upon arrival at Mars, the piloted vehicle will rendezvous with the cargo vehicle in Mars orbit. Four crew members will transfer to the Mars Lander Vehicle and depart for a 20-day exploration of the Martian surface. The four remaining crew members will perform the propellant transfer from the cargo to piloted vehicle, conduct Mars-orbital science, and monitor and assist the activities under way on the surface of Mars. After a total of 30 days in the Martian system, the surface crew will rendezvous with the orbiting piloted vehicle to depart for Earth, arriving about 5 months later. Total mission length is 440 days.

Cargo/piloted vehicle pairs will again be launched to Mars during the next two launch opportunities (2009 and 2011). The third piloted flight, in 2011, has a total round-trip flight time of 500 days. This longer flight time was necessary to avoid prohibitive mass penalties associated with the sprint trajectory in 2011. (The sensitivity of Earth-Mars trajectories to launch opportunity is discussed in the CONCLUSIONS AND OPPORTUNITIES section of this report.) Piloted excursions to Phobos and Deimos are envisioned as part of the first two Mars expeditions. Each of the three Mars landing missions will also visit a different site on the Martian surface.

## Results

The Mars expeditions will deliver a crew of eight to Mars, with four landing on the surface, but arrivals will begin almost five years later than the Phobos expedition. This difference results from the fact that the Mars case is of a much larger scale, with increased dependence on infrastructure and new technologies. The Mars expeditions will require significant LEO infrastructure and a substantial degree of on-orbit assembly operations at a LEO transportation node.

The Mars expeditions are more complicated than the Phobos expedition from several standpoints. Separate cargo and piloted vehicles must be built to land on (cargo and piloted) and ascend from (piloted) the Mars surface, significantly increasing the vehicular infrastructure complexity (and resultant IMLEO) for these missions. Mars EVA operations will require new pressure suits, portable life support systems, and surface transportation systems which can safely and productively operate in the Mars one-third gravity, nonvacuum environment. The fact that the Mars Expeditions launch to Mars over three successive opportunities introduces significant astrody-

namic effects into the analysis. Substantial variations in mission  $\Delta V$  requirements, and corresponding IMLEO, occur as a result of the heliocentric trajectory sensitivity to launch year. The doubling of crew size from four (for Phobos) to eight for the Mars Expedition also introduce a level of complexity to the mission design.

Due to the extremely large annual LEO mass requirements (peak year mass = 1,770t), two of the major drivers affecting these expeditions are the Earth-to-orbit (ETO) level of activity and LEO assembly techniques.

It is important to acknowledge here, however, that the IMLEO estimates to support the three missions associated with this particular case study are unrealistically high. It is also important that in deriving these estimates, the supporting analysts obtained a cause-and-effect knowledge base of the various transportation and surface systems element/trajectory sensitivities that drove IMLEO to these high levels. This knowledge should enable substantial reductions in IMLEO estimates for future Mars system expeditionary case studies.

## Lunar Observatory (Case Study 3)

The objective of this case study is to understand the effort required to build and operate a long-duration human-tended astronomical observatory on the far side of the Moon, and also to conduct regional lunar exploration. The astronomical facility will consist of radio and optical telescope arrays, stellar monitoring telescopes, and radio telescopes. Such facilities offer the potential of several orders of magnitude improvement in resolution over Earth-based or orbital facilities, and, in some cases, provide unique observing environments not available anywhere else in the solar system. Also included is a program of geophysical stations, the capability for local geological traverses, and a modest life sciences laboratory.

## Mission Description

This case study assumes that four missions to the Moon's far side will be required to set up an operational facility. The four set-up flights will consist of one cargo and one piloted mission per year, in two successive years, beginning in 2004. The four set-up missions will be followed by one operational crew mission per year thereafter. The scenario for this case study is illustrated in Figure 7.

Each piloted mission will carry a crew of four. The round-trip flight time will be less than 20 days, including a maximum of 14 Earth days spent on the lunar surface. No permanent habitat facility will be developed; because of the short surface stay time, and also because of the fact that subsequent missions will visit different sites, the crew will live in and work out of the lander vehicle on each mission.

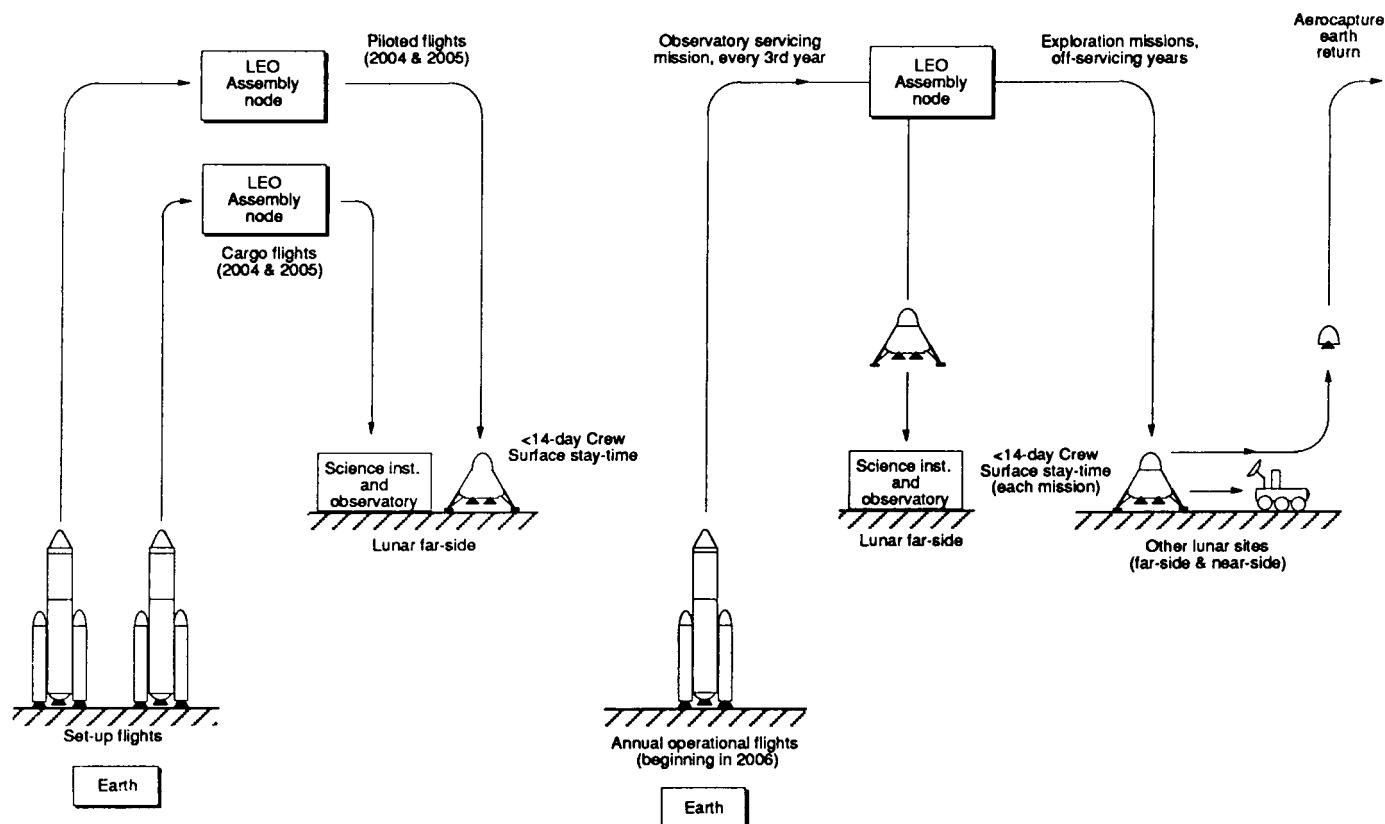


Figure 7.- Lunar observatory

Nominally, the astronomical facilities will require human-tended servicing only once every three years after they become operational. In the off-servicing years, crews will explore other lunar sites. During these exploration sorties, crew members will make several trips in an unpressurized rover for distances up to 10 kilometers.

## Results

This case study emphasizes a maximum scientific return using a minimum amount of permanent support facilities. Significant human interaction will be required to assemble, deploy, operate, and service the array of instrumentation planned for this facility. In addition, once the facility is operational (in 2005), subsequent crews will be utilized for local geological exploration, scientific excursions in rovers for distances up to 10 kilometers, and upgrades and sensor/receiver instrumentation changeout at the observatory.

This scenario can be accomplished for less than one-fourth the total mass required for the Mars expeditions case. The Lunar Observatory will be operational in two years, using approximately the same mass investment as the Phobos mission. Furthermore, user allocation mass is 100 metric tons during the first 10 years, which is twice the allotment for the Mars expeditions.

This case requires a facility in LEO to house the crew and support transfer vehicles and payload assembly operations, including element construction and checkout, propellant storage and transfer, and payload servicing.

The major drivers for this scenario are the planetary surface activities requirements, including surface power systems and EVA technology. The science facilities on the Moon require the deployment of large, complex arrays, and special equipment is required for their emplacement. Certainly, robotically assisted assembly and construction will be promising new technologies to investigate.

## Lunar Outpost to Early Mars Evolution (Case Study 4)

This case study builds a capability that leads to the development of a self-sufficient, sustained human presence beyond low-Earth orbit. The evolutionary approach provides the basis for continuing technology advancement, experience in outpost development and habitation, use of local resources, and the development of a facility with opportunities for further growth. This is accomplished in two phases: the establishment of a permanently staffed facility on the Moon, progressing to the establishment of a similar outpost on Mars. The case study was constrained by a limitation of mass to LEO in

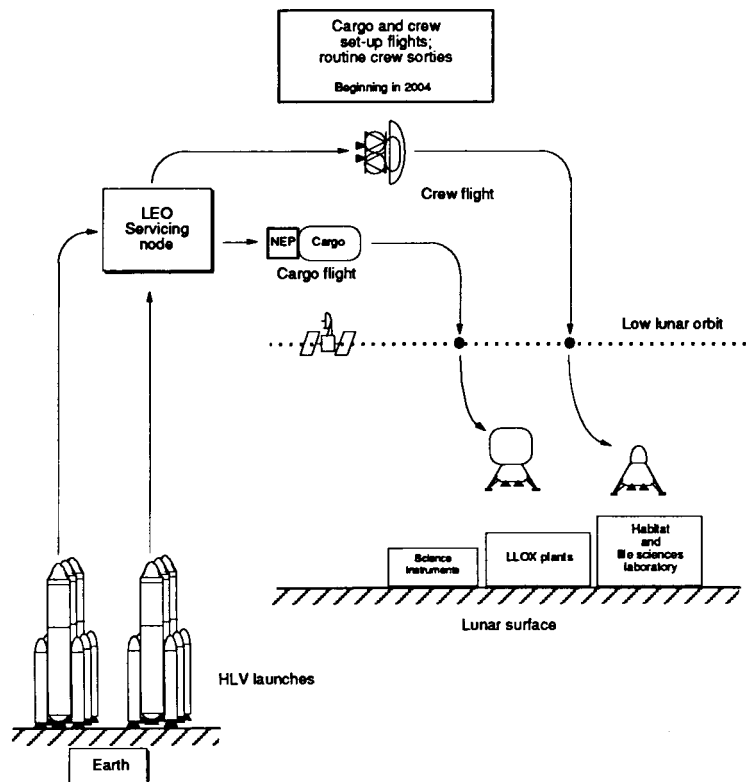


Figure 8.- Lunar Outpost to Early Mars Evolution—lunar portion

order to promote creativity in new technology applications and in-situ resource utilization.

The lunar phase of the mission includes the development of a lunar science and resource outpost, which is dominated by a lunar liquid oxygen plant, local-to-regional geological exploration, and a life sciences laboratory for conducting fractional-gravity research. Because the location of the outpost may be dictated by resource and operational considerations, and not observational science, a far-side site is not mandatory.

Cargo and piloted lunar space vehicles will be used to optimize delivery of payload and crew exchange. The lunar outpost will be capable of permanent habitation, and crews will occupy it for periods of six months to a year between rotations.

Subsequent to the development and operation of the lunar facility, and after a knowledge base for extraterrestrial human habitation is established, human exploration missions to Mars will be undertaken. Oxygen produced on the Moon will be made available for the Mars spacecraft, which depart from the Moon to Mars via an Earth flyby injection maneuver. Conjunction-class trajectories are used, with separate cargo and crew vehicles. These trajectories require approximately one year of stay time in the vicinity of Mars, either in orbit or on the surface.

The emphasis in these scenarios is the local-to-regional geological exploration of the surface of Mars, using piloted and robotic mobility systems, and the exploration of Phobos and Deimos, with the objective of establishing the capability to extract propellant from one of the moons to support subsequent missions. The study envisions three missions to the Mars system, each to a different site, in preparation for the establishment of a permanent outpost on Mars.

### Mission Description

Beginning early in the next century (approximately 2004), a series of piloted and cargo flights will embark for the Moon. As illustrated in Figure 8, the crew will transfer to the Moon aboard chemically propelled transfer vehicles, whereas the surface equipment will be transported via an Electric Cargo Vehicle. Several years will be spent in constructing a permanently staffed surface facility. Experience will be accumulated in all aspects of long-duration human planetary exploration missions: life sciences, psychological effects and human dynamics, exploitation of natural resources, and scientific exploration. One goal of the base is to produce, from the lunar soil, the liquid oxygen needed for subsequent Mars flights.

In approximately 2010, the branch to Mars will take



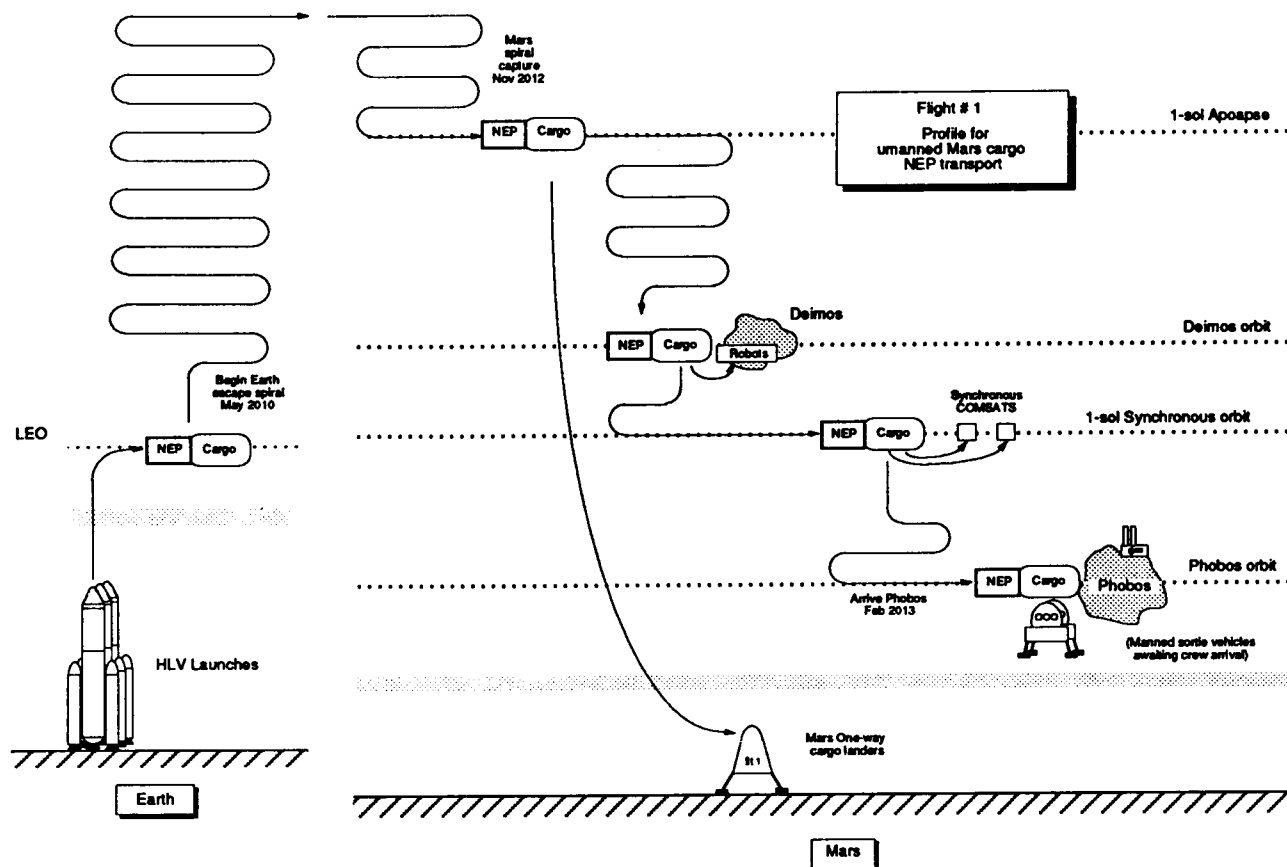


Figure 9.- Lunar Outpost to Early Mars Evolution—Mars portion

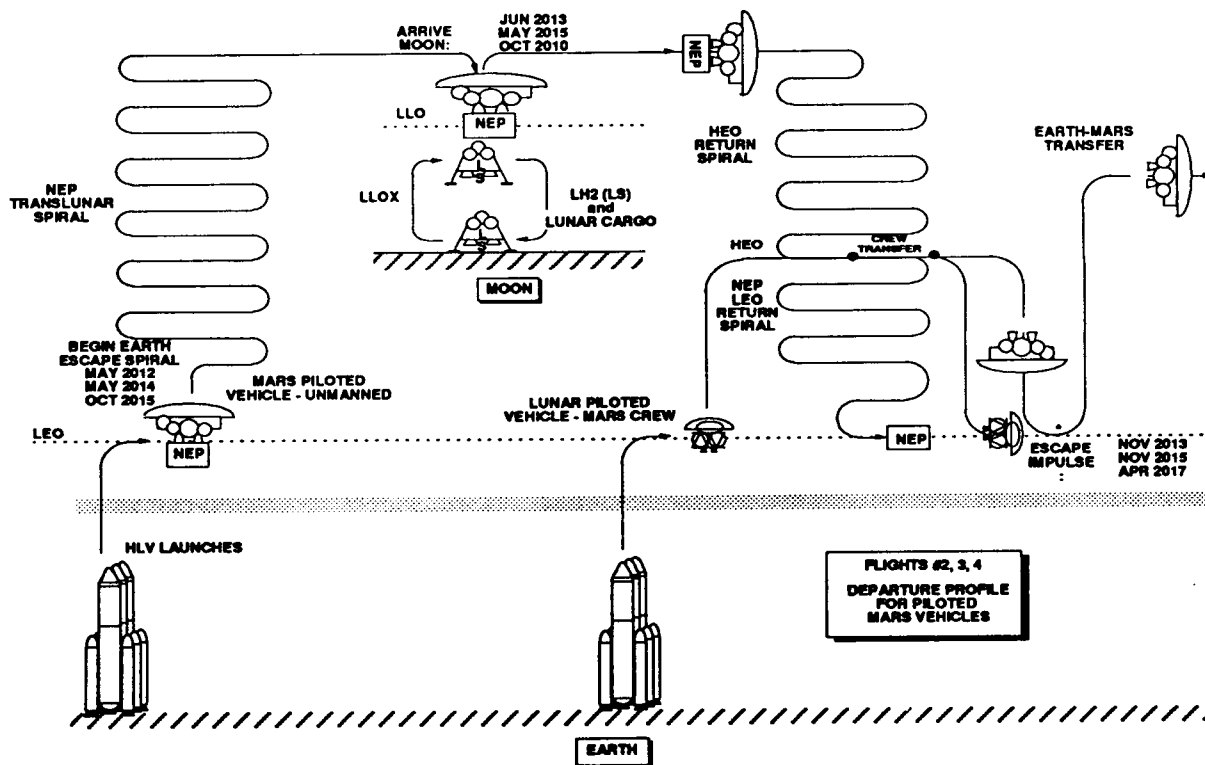


Figure 10.- Lunar Outpost to Early Mars Evolution—Mars portion (flights 2,3,4 - Earth orbital and lunar operations)

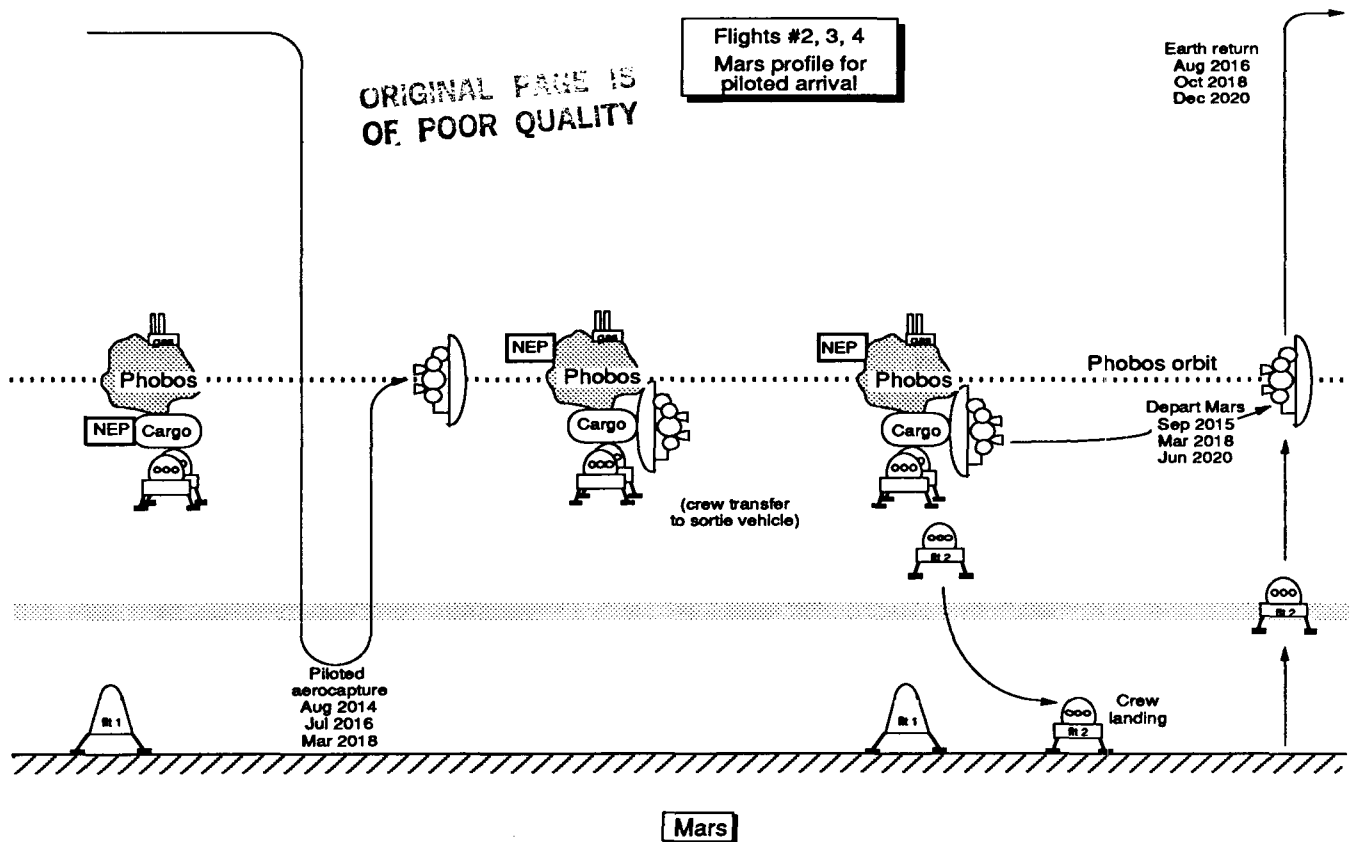


Figure 11.- Lunar Outpost to Early Mars Evolution—Mars portion (flights 2,3,4 - Mars orbital operations)

place; the nominal scenario for this phase is depicted in Figures 9, 10, and 11. The specific timing is left open, but in general would occur when the lunar capability is sufficient to provide enough propellant to enable the Mars mission. First, an Electric Cargo Vehicle will carry the Mars surface equipment, excursion modules for transportation between Mars and Phobos, and various types of scientific equipment to the Mars system. As the spacecraft approaches the Mars system, it will drop off communications satellites in synchronous orbit, send robotic explorers to Deimos, and, upon arrival at Phobos, deposit a system for producing fuel. Liquid hydrogen and liquid oxygen propellants produced on Phobos will be used later in the scenario.

In the next Earth-Mars launch opportunity, a second Electric Cargo Vehicle, reused from the lunar portion of the mission, will push an (unmanned) crew transport to the Moon for fueling with lunar liquid oxygen. After fueling, the cargo vehicle leaves lunar orbit with the fully loaded Mars personnel vehicle, and, when in cislunar space, separates and begins its return to a lower orbit about Earth, where it will await reuse on the next ferry mission. The first crew is transported to the piloted Mars transfer vehicle, and after systems check, they begin their journey to Mars. The nominal plan is for the crew to stay at Mars approximately one year, and return to Earth after

a total mission time of nearly three years. Options exist for the crew to perform a flyby abort mission (if a problem occurs, the mission can return to Earth without landing on Mars, after a total trip time of about 600 days), or to limit their stay at Mars to up to 60 days. A third option exists for a two-year stay at Mars.

Piloted excursions to Mars, similar to the first described above, are anticipated in the ensuing launch opportunities. Further cargo flights will be necessary over the duration of the Mars base build-up.

## Results

The evolutionary case study places major demands on the low-Earth orbit operational facilities to assemble, refuel, maintain, and service interplanetary vehicles. The facilities will also be used to transfer substantial quantities of propellants arriving from Earth, and will serve as a transfer facility for crews going to and returning from planetary missions.

This case study also requires orbital staging and refueling operations in low lunar orbit, as well as in the vicinity of Phobos. The electric cargo vehicle serves as a mobile node for operations outside low-Earth orbit; therefore, nuclear electric propulsion system technology to power

the electric cargo vehicles is a major requirement. Systems and techniques for aerocapture at Mars and Earth are also needed.

Life sciences precursor missions and studies must resolve the issue of zero gravity versus artificial gravity for extended voyages to Mars. In this case study, that research is performed in the one-sixth gravity of the lunar surface and at the LEO node. For permanent lunar and Mars bases, maximum possible closure of life-support systems must be provided, and significant improvements over Space Station Freedom life-support systems are desirable for Mars transfer vehicles.

The self-sufficiency embodied in this case levies a requirement for the development of technology and systems for mining, processing, and storing local resources. Significant power levels to operate surface habitats, systems, and rovers are required; of necessity, nuclear power sources like that of the SP-100 program are the most promising candidate technologies. However, extensions to the multi-megawatt range must be made.

# The Search for Leverage

In addition to the system and element definition studies performed in connection with specific case studies, the FY 1988 activities also included special studies, reports, and assessments in areas that offer potential leverage beyond the baseline scenarios. In the broadest sense, "leverage" refers to any savings or benefit accrued from the incorporation of an option into a baseline scenario. For example, the use of advanced propulsion technologies is a strategy for reducing initial mass in low-Earth orbit (IMLEO). The degree of leverage can be measured in terms of savings of or benefit to many quantities in addition to mass, such as: power, volume, man-hours, consumables, data returned, complexity, and dollar cost. In a systems engineering sense, leverage is used to optimize the objective function.

The choice of the objective function(s) will determine areas in which the search for leverage will concentrate. FY 1988 activities focused on IMLEO as the objective function; therefore, the search for leverage concentrated on strategies and technologies that could minimize this parameter. Preliminary study results, detailed in the pages that follow, have provided an overview of broader issues involved in the use of a number of potential strategies and technologies. Although final conclusions will require further study and analysis, the process for doing so in FY 1989 has been defined through this effort.

Several technologies and techniques were selected for special emphasis. These activities can be divided into six topical areas: (1) extraterrestrial resources, (2) in-space vehicle processing, (3) advanced propulsion, (4) surface operations, (5) surface systems, and (6) cost understanding.

**Extraterrestrial resources** addresses the concepts of the benefit and requirements of using in-situ resources for propellant or for commercial exploitation. The potential for the extraction and production of fuel exists for all targets of FY 1988 case studies; a preliminary methodology was formulated through which in-depth analyses can be initiated. A second area that was examined is the possibility of using helium-3 produced on the Moon as a fuel for future nuclear fusion reactors on Earth.

The second general area addressed by this year's trade studies is **in-space vehicle processing**, a topic of great significance to the feasibility and complexity of human exploration missions. Study activities examined five specific aspects: (1) general strategy, (2) assembly of the Phobos spacecraft in LEO, (3) issues involved in Mars-orbital refueling, (4) launch of cryogenic propellant storage tanks, and (5) transportation nodes.

**Advanced propulsion systems**, particularly those that derive power from nuclear sources, were applied to the Phobos, Mars, and evolutionary case studies to assess the benefit of such systems to those cases.

**Planetary surface operations**, the fourth area, covered technologies and techniques required by case study plans for activities conducted on, or in the near vicinity of, potential planetary target bodies. Specific emphases included: the feasibility of automating lunar LOX production, teleoperated planetary rovers, and special requirements related to the exploration of Phobos. Closely related to surface operations is the fifth area, **surface systems**, which examined lunar surface power and advanced life support.

The sixth area, **cost understanding**, was a special emphasis study. Each of these six topical areas is described in more detail in the pages that follow.

## Extraterrestrial Resources

**Propellant Production.** Augmenting Earth-supplied propellants with those derived from the Moon, Mars, and/or Phobos and Deimos inherently offers potential as a high-leverage technology. However, determining the viability of extraterrestrial propellant use is exceedingly complex, since it involves a large number of interdisciplinary and tightly interrelated variables. To analyze these variables, it is necessary to understand space development options to a level of engineering and programmatic detail that does not currently exist. These variables also tend to change dramatically with each specific case. Therefore, the viability of the use of extraterrestrial propellants, and the associated implementation plan, must be demonstrated for each case study independently.

A key finding is that in-situ propellant production is beneficial only for long-term development: the facilities start-up can take a long time to achieve full production capability, and the payback is only realized over a 10- to 20-year horizon. Not surprisingly, then, lunar LOX usage for the round-trip LLO/lunar surface indicates increased costs in the short term, but a savings of about 30 percent (in terms of mass) over the long term. Using rough approximations for surface production facility masses, the use of propellants derived from Mars, Phobos/Deimos, and the Moon demonstrates varying degrees of benefit as applied to IMLEO. For example, preliminary assessment indicates that Phobos/Deimos propellant for the return leg offers more savings for chemical propulsion systems than lunar LOX for outbound legs to Mars. Also, Phobos/Deimos propellant may be beneficially

exported to LEO, whereas export of lunar LOX to LEO via chemical propulsion systems may not be beneficial.

Further study concerning the viability of extraterrestrial propellant production must address the issue of the location of a transportation node in Earth-Moon space. The use of lunar LOX appears to significantly reduce the IMLEO requirements for manned Mars missions. However, it also significantly increases the amount of lunar LOX required if the transportation node is located in LEO, due to the transportation of the mission LOX from the Moon to LEO. Previous studies have concluded that it would be difficult to deliver lunar LOX to LEO at a lower cost than from the Earth's surface. This signals the obvious linkage between extraterrestrial propellant use and the location of an Earth-Moon transportation node.

**Lunar Helium-3 Utilization.** A workshop was conducted to provide information assessing the feasibility, practicality, and advantage of using helium-3 (He-3) extracted from the lunar regolith to fuel future nuclear fusion reactors on Earth. Experts from the nuclear fusion, mining, and lunar science communities participated. The workshop centered around two topics: terrestrial fusion technology, specifically as it pertains to He-3 applications, and the technology required to mine He-3 from the lunar surface.

The group concluded that mining, beneficiation, separation, and return to Earth of He-3 from the Moon are possible, but would require a large-scale infrastructure and improvements in technology. Lunar oxygen production plants would provide an early technology demonstration (2010-2020) for He-3 production by developing lunar soil mining and processing techniques and by providing an opportunity to produce some He-3 as a by-product of the lunar oxygen production process. This is in keeping with the estimated timeframe in which deuterium/helium-3 fusion could possibly be ready for commercial terrestrial energy production (circa 2015).

### **In-Space Vehicle Processing**

**General Strategy.** Earth-to-orbit delivery of space transfer vehicles is a major architectural, configuration, and operations consideration. When these transfer vehicles become of such a size that it is no longer possible to launch them on a single flight of an established ETO vehicle, many alternatives exist, each with its own set of specific needs and impacts. A major challenge in the design of the architecture (including infrastructure) and configuration for each class of exploration mission will be the incorporation of the proper emphasis and balance between needs arising from mission objectives and those derived from placing the system into service: i.e., assembly. The lessons learned in designing Space Station Freedom will be used to gain initial insight into the

proper emphasis that should be placed upon a "design for assembly" philosophy.

A trade exists between on-orbit assembly and launch vehicle capability. Considerations that must be included relate to development cost, total operational support cost, and number of vehicles to be produced. A future pursuit will be to determine whether these considerations can be correlated to ETO delivery capability, and thus, whether a cost-optimized ETO payload-to-orbit capability can be derived.

Most historical data on the final assembly of spacecraft lie in the flows conducted for assembly of current and past vehicles at the launch center. It was assumed in this year's studies that LEO node operations for assembly and verification will be similar to current ground-based activities for such tasks. Further, it was assumed that all operations that can be done on the ground will be done on the ground, and extravehicular activity will be used only when necessary. Flight elements will be fully tested prior to launch to LEO, and will be designed and built to facilitate on-orbit assembly. Early analysis indicates the need for modularization to enhance in-space vehicle processing.

Final installation of hazardous materials is most safely done off-node and as close to stage ignition as possible. It is also desirable for propellant loading to be performed in this period. These considerations need to be examined in relation to the proposed Phobos mating strategy, in which fully fueled propulsion stages are launched to orbit and mated, with the entire launch stack build-up requiring more than one year.

Processing spacecraft on the ground requires several weeks and several hundred people for each vehicle. Since this will be difficult to duplicate on orbit, it is likely that things must be done differently during LEO transportation node operations, including the use of automation and telerobotics. It is unreasonable to assume that robots in space will take over the assembly tasks that are currently done on space shuttles at Kennedy Space Center. However, robots may ease the assembly burden for well-designed processes. To date, trades simply assume that many tasks can be automated and/or done by using teleoperation and artificial intelligence. Such assumptions will require considerable study to assess their validity and to determine the design characteristics necessary to facilitate the use of automation and teleoperation.

A workshop was held in which participants assessed robotics requirements for the OEXP case studies, evaluated the feasibility and adequacy of current technologies, projected the magnitude of advances over a period of 10 to 15 years, and identified barrier, as well as high-leverage, issues in the OEXP case study formulation. There

was a strong feeling among workshop participants that, with appropriate care in the design of components and the assembly process, many tasks are largely achievable with robotic technology. In some cases, automation is an enabling technology; i.e., if the tasks cannot be automated they must be deleted from the flows. In other cases, the use of automation and teleoperation allows a simplification of effort and a substitute for crew time; therefore, these technologies are considered to be enhancing.

Another factor in the in-space vehicle processing strategy is that the LEO node will strongly influence the character of assembly operations. The amount of functional support that this facility provides to both the vehicle being assembled, and the assembly process itself, will be a significant factor in the overall design.

The location of the LEO support crew base will have a major impact on operations. System functionality requirements will differ significantly, depending on whether the assembly crew is based at Space Station Freedom and ferried to the assembly node, located at the LEO assembly node facility itself, or located in the piloted Mars vehicle. If the crew is based at Freedom or in the Mars vehicle, the LEO node will need to be designed as a man-tended system.

The flight rate requirements for ETO transportation for the human expeditions are very high, particularly for operations support. The high flight rate is anticipated to impact virtually all major operations phases, including launch vehicle processing and cargo integration, flight planning and reconfiguration, launch preparation, and launch and mission support. The utilization of multiple launch systems, such as an unmanned heavy-lift launch vehicle in combination with the Space Shuttle, can be expected to introduce additional complexity. An interesting point is that the LEO assembly operations may be representative of the assembly operations required by exploration missions, using similar technology, en route to other solar system destinations. Extrapolation of these results to assembly operations at non-LEO sites in space may also be possible.

**Assembly of Phobos Spacecraft in LEO.** A variety of previous LEO transportation node studies have concentrated on the problems of assembling, refurbishing, and maintaining fully or partially reusable transportation systems for translunar or trans-Mars flight. This previous work has concentrated on scenarios which assume a substantial LEO infrastructure. The capabilities for on-orbit bit assembly and test of spacecraft, as well as cryogenic propellant transfer and storage, are in general assumed.

On the other hand, the infrastructure and many of the

technologies needed to assemble, test, and launch large spacecraft from LEO do not exist at present, a lack which poses an obstacle for proposed missions carrying humans to Mars with Earth departure dates on or around the year 2000. The Space Station Freedom Program's Evolution Working Group is now working to characterize the projected use of the phase II station. Among the important issues being addressed is how Space Station Freedom might evolve into a transportation node in support of exploration-class missions.

It is crucial to long-term program planning that this working group closely examine the technical, operational, and scientific research ramifications of using the station to support assembly of large space transfer vehicles in the 1000-t range. From this study a determination will be made of whether it would be advantageous to branch to a second LEO node and when to do so.

An OEXP study addressed the potential for assembling the Phobos cargo and piloted space transfer vehicles in LEO without the use of a transportation node or other space-based infrastructure of significance (the required baseline for the Phobos Expedition Case Study). Various Phobos vehicle assembly concepts were analyzed, and a list of key issues was created, the solutions to which will largely determine the feasibility of this approach. The general consensus was, however, that it will be extremely difficult to assemble the Phobos mission spacecraft without on-orbit strongback, remote manipulator, and EVA/IVA crew support.

**Issues Involved in Mars-Orbital Refueling.** The expeditions to Phobos and Mars assume that a cargo vehicle carrying the piloted vehicle's return propellants has preceded the piloted vehicle into Mars orbit. Cryogenic fluid transfer between vehicles in Mars orbit is the assumed baseline for these case studies. Several other potentially viable propellant transfer options were identified during this study year but require further technical analysis before specific changes to the baseline could be recommended. These options include transfer of fully loaded propellant tanks between cargo and piloted vehicles as well as transfer of the pressurized crew habitat module to a man-rated cargo vehicle, creating a new piloted vehicle.. Technical areas requiring further penetration for each option include advanced technology requirements, support equipment and power requirements, transfer time requirements and overall operational complexity, vehicle commonality and physical interface considerations, and overall impact to IMLEO.

**Launch of Cryogenic Propellant Storage Tanks.** A question addressed in FY 1988 was whether the better method of launching cryogenic fuel to LEO is to launch fully fueled flight tankage or to use separate transfer tanks. Cryogenic flight tanks (integrated to the transfer

vehicle propulsion system) are typically not designed for long storage. Therefore, due to the poorer thermal insulation, boil-off losses are higher, resulting in a mass penalty in terms of additional propellant to accommodate the excess tankage weight and boil-off reserve for a Mars mission. An alternative solution would be to increase the thermal insulation of the flight tankage to reduce boil-off, but this solution, like the first, increases the initial Mars injection weight of the spacecraft.

The alternative mode of launching separate heavily insulated storage tanks with transfer to the lighter weight flight tankage just prior to stage ignition reduces both the Mars-injection weight and the ETO lift requirements of the Mars vehicle. However, this mode requires the separate launch of the fully fueled storage tank. The trade-off that needs further study is the assumed higher ETO requirements for this mode versus higher injection mass requirements of the previous mode.

**Transportation Node.** A final topic related to In-Space Vehicle Processing is the need for a transportation node and the choice of its location in Earth-Moon space to support and/or enhance human exploration initiatives. The use of a transportation node, its location, and its assigned functions significantly impact overall mission performance. For FY 1988, this study was conducted for the Lunar Observatory and evolutionary case studies.

For the Lunar Observatory case, four alternatives were examined: no node, LEO node only, low-lunar orbit (LLO) node only, and nodes in both LEO and LLO. For the baseline mission in which vehicles will require fueling and assembly on-orbit, the case without a node is considered impractical. If any reusable vehicles are employed, a LEO node becomes mandatory for storage and maintenance between missions. Therefore, a LEO node was assumed to be required for the Lunar Observatory case.

Because of its location, a low-lunar orbit node cannot serve as a substitute for a LEO node. The only issue to be considered is whether a low-lunar orbit node should be included in addition to a LEO node. Since the Lunar Observatory case does not assume the use of local resources, the principal reason for a node in lunar orbit does not apply, but such a node can perform other functions. However, many of the tasks envisioned for an LLO node could be more easily accommodated by dedicated lunar orbiters. Furthermore, the LLO node would increase costs, integration, and operational complexity, requiring an additional rendezvous and docking operation upon arrival in lunar orbit, and it serves no function at all for the two cargo missions. Therefore, for the Lunar Observatory case: (1) a LEO node is highly desirable, if not essential, and (2) there is no plausible reason for an LLO node.

For the evolutionary case, the objective was to determine the most desirable location in Earth-Moon space for supporting the transportation needs of the Mars portion of the scenario. The study assumed that a transportation node is justified, based on the specifics of the case study, and that the scope of this trade is to analyze only the location of this node. Other key assumptions include: all vehicle traffic to LEO assumes aerocapture at Earth, and lunar liquid oxygen (LOX) was assumed to be available to fuel the vehicles bound for Mars, as well as the tankers carrying fuel to the transportation node.

Five candidate node locations are broadly representative of the major options in Earth-Moon space. These options include: low-Earth orbit, geosynchronous Earth orbit; Earth-Moon libration point (L1); low lunar orbit (LLO); and an elliptical orbit, with perigee at Earth and apogee at lunar distance from Earth. The analysis for this case study assumed the use of lunar LOX even for the LEO node.

Within the limitations implied by the validity of the specific set of assumptions used, only the following observation was made:

Positioning the node in "near-lunar" space (L1, LLO, elliptical orbit) appears to be a better choice for steady-state operations if lunar LOX is utilized; these locations (theoretically) result in an advantage over a node located in "near-Earth" space, in terms of reduction in LEO mass, mission LOX requirements, and LOX transport requirements.

### Advanced Propulsion

Propulsion concepts with high specific impulse and high spacecraft thrust-to-weight are very desirable. For the most part, near-term technologies such as chemical and electric propulsion have one, but not both, of these desired attributes. In the future, "high-leverage" technologies may be available that will allow large quantities of cargo to be transported quickly over interplanetary distances. To assess the leverage that advanced propulsion technologies could provide to NASA missions, a large number of nonchemical propulsion system designs ranging from near-term nuclear electric propulsion (NEP) systems to solar-system-class inertial fusion rockets were examined.

In general, electric propulsion systems were found to occupy a region of parameter space where the specific impulse and mass are about 2 to 10 kiloseconds and about 10 to 50 kg/kWj, respectively. With an engine thrust-to-weight of approximately  $10^{-4}$ , electric propulsion systems appear to be well-suited for flights to the Moon and for interplanetary cargo missions, where short trips are not a high priority. Solar and laser thermal rocket concepts

offer some advantages in orbital transfer vehicle trip time over electric propulsion systems, but at the expense of reduced payload fraction.

However, electric propulsion systems are not particularly economical for short flight-time trajectories, such as the sprint. A 200 mWe ion/nuclear electric propulsion system, with specific mass and impulse of about 1 kg/kWj and about 20,000 seconds, respectively, was examined for its quick trip potential. The system was capable of a 7.5 month round-trip mission to Mars, but its initial mass was about 1,500 metric tons (t) and the propellant and payload fractions were 80 percent and 6 percent, respectively. At a 400 mWe power level, six-month round-trip times could be achieved, but only for a zero payload fraction.

Of the various concepts that could be developed over the next two decades, solid and gas core nuclear thermal rockets offer some of the best prospects for sprint missions. Solid core technology and significant research into gas core feasibility issues were demonstrated during the Nuclear Engine for Rocket Vehicle Application (NERVA) program, adding to the technical maturity of these concepts.

High-power solar and laser thermal concepts, and advanced technology solar/nuclear electric propulsion (approximately 1 to 5 kg/kWj) may enable these concepts to also break into the sprint-class region. However, solid and gas core nuclear concepts (and potential hybrid configurations) appear to be the leading contenders in this category at this time. Beyond the year 2020, the introduction of high thrust/high specific impulse magnetic and inertial fusion rockets could make solar-system-class spacecraft a reality.

In terms of technology maturity, the solid core nuclear thermal rocket (NTR) is the only propulsion concept to be experimentally tested at the power, thrust and specific impulse levels (about twice those of the best chemical engine) required for a Mars mission. During the NERVA program this technology was developed to a near-operational status with a total of 19 rocket reactors being built and tested. Included among these systems were a 250 klbf thrust engine (Phoebus-2A) and a fully integrated experimental prototype engine (the XE-P) both test-fired in the late 1960s. Applying NTR with a specific impulse of 850-950 seconds and thrust levels of 100-250 klbf to the OEXP case studies leads to the following findings.

**Benefit to Phobos Expedition.** Compared to chemical propulsion, the use of NTR technology for the "all-propulsive" split/sprint Phobos mission results in a 44 percent decrease in total IMLEO. Approximately 50 percent of the mass savings is attributed to reduced propellant consumption by the piloted vehicle. The

propellant requirements for the single stage cargo vehicle are also reduced by more than by 50 percent when compared to the chemical case. With a propellant loading of approximately 136 t, the cargo vehicle very closely resembles NTR stages studied in detail by NASA contractors during the 1960s and early 1970s for lunar and interplanetary applications. Logistics for the Phobos mission are also simplified using NTR technology: instead of five vehicles/stages, only three are required.

Increasing the specific impulse from 850 to 950 seconds provides a further increase in total mass savings of about 130 t. At 950 seconds, the IMLEO is 49 percent of the reference chemical results. Total engine burn time for the 250,000 lbf class NTR used on the cargo vehicle is on the order of 15 minutes. The Phoebus-2A rocket/reactor operated at a thrust level of 200,000 lbf for approximately 12.5 minutes during its full power test in 1968.

Increasing the engine thrust level from 100 to 250 klbf on the trans-Mars injection stage increases the total mass of the piloted vehicle by only 14 t. The spacecraft thrust-to-weight is increased, however, by more than a factor of two, and the engine burn time for the trans-Mars injection stage is reduced from 51.0 minutes to 21.5 minutes, which minimizes gravity losses during the maneuver.

**Benefit to Mars Expeditions.** With a specific impulse of 900 seconds, the "all-propulsive" NTR option provides a total mass savings on the order of 10 percent over the aerobraked/chemical mission profile results. This savings is accrued totally by the cargo vehicle; the piloted vehicle mass is higher than its aerobraked chemical counterpart. However, it is possible to show a mass savings for the piloted vehicle by eliminating the cooldown propellant for the expendable trans-Mars injection stage and increasing the specific impulse to 950 seconds.

**Benefit to Evolutionary Scenario.** For the same trip times, the use of closed-cycle Nuclear Light Bulb (NLB) gas core technology allows the cargo/sprint missions to be performed "all-propulsively" with a lower launch mass in Earth orbit than that required by the NEP cargo and aerobraked chemical systems launched from lunar orbit. The mass reduction is approximately 414 t, which represents a savings of approximately 21 percent. The logistical complexity of the mission and of lunar base operations is also reduced. In the reference case study, a total of six vehicles/stages are involved in preparing and transporting the cargo and crew from lunar orbit to Mars. A total of approximately 840 t of lunar LOX must also be produced to fuel the logistics landers, excursion modules, and piloted vehicle stages used during the Mars mission. With NLB technology, a single stage cargo vehicle and a two-stage piloted vehicle are all that is required. Because the NLB requires only  $\text{LH}_2$  propellant,



the infrastructure for producing, storing, and ferrying up approximately 840 t of lunar LOX is unnecessary, and can be used to support other lunar base activities.

A single crew/cargo round-trip vehicle employing space radiator-cooled, open cycle gas core rocket (SRGCR) technology can perform "all-up," all-propulsive, exploration-class missions to Mars in approximately 280 days (including a 40-day stay at Mars) with an IMLEO of approximately 1,000 t. Increasing mission time to approximately 450 days (the duration of the split mission sprint leg) lowers the IMLEO to approximately 600 t. With the SRGCR, a separate cargo launch is unnecessary, and significant reductions in both mass and in number of required vehicles/stages are possible.

## **Surface Operations**

**The Feasibility of Automating Lunar LOX Production.** In support of extraterrestrial propellant production, the feasibility of automating the operations of digging, transporting, and processing lunar soil and operating a lunar LOX production facility was examined. The exploitation of lunar resources is a high-leverage item because: (1) the production of lunar LOX provides an on-site source of oxygen for rocket fuel and for life support, and (2) studies indicate that oxygen exists in sufficient abundance at the lunar surface to meet these needs.

The oxygen on the Moon appears to be most often bound in the four oxides  $\text{FeO}$ ,  $\text{SiO}_2$ ,  $\text{Al}_2\text{O}_3$ , and  $\text{TiO}_2$ . Oxygen can be extracted by chemical, electrolytic, and pyrolytic processes. The emphasis in this study was to verify the possibility of the automatic acquisition, in sufficient quantities, of the appropriate lunar material and its automatic delivery to the chemical plant for the production of LOX.

Lunar soil is generally fine-grained; therefore, heavy digging and crushing appear to be unnecessary. A mining volume of 12,000 metric tons per year for 15 years will require an area of approximately 100,000 square meters, if the average depth mined is about 2 meters. The facilities emplaced by the crew would consist of a continuously operating bucket wheel, similar to operations performed in strip mining on Earth. Conveyor belt systems are used to bring the material to the processing plant. At most, 9 percent of the processed material is extracted and converted to LOX; the remaining 91 percent is redeposited on the lunar surface by a conveyor that moves behind the bucket excavator at the same forward speed. The technology required for continuous autonomous operations is already being used on Earth.

**Teleoperated Rovers in Support of Human Planetary Missions.** Teleoperated rovers, like humans, can be important scientific and operational tools for exploration

of lunar, Martian, and Martian satellite surfaces. However, it is important when designing missions which utilize both rovers and humans that the rovers' science and operational objectives take advantage of the synergistic aspects of humans and rovers working together.

Whether through acquisition of quality science data from selected or serendipitous locations beyond the landing or crew habitat site, through improvement in the effectiveness and efficiency of surface exploration and base-camp operations by mechanical or electronic advantage, or through reduction of environmental risks to the mission crew, it is important that the man-machine team be assigned tasks which can be accomplished better jointly than either man or machine is capable of accomplishing individually.

Mission planners should capitalize upon the physical and electronic advantages of an immediate crew presence. A surface crew in close proximity to the rover and its environment will be in an excellent position to respond to both routine and contingency situations requiring timely human judgment. A crew member can immediately process and integrate direct visual, electronic, or intellectually derived data and make a decision based not only on logic and deduction, but on judgment and knowledge of peripheral mission systems and operations status. Additionally, as advances in automation and robotics technology allow rovers to perform more and more 'outside' operational tasks independent or remote from the crew, total EVA time is reduced as is overall environmental risk to the crew.

Additional factors which may influence the general utility of teleoperated rovers are overall mission objectives, rover operational availability, and mission duration. Expedition-class missions such as those of the Human Expedition to Phobos Case Study allow only about 30 days in the immediate Mars vicinity for a crew of four. During this period, two crew members spend  $\leq 20$  days on or in the immediate vicinity of Phobos. Two other crew members remain with the mothership in Mars orbit to maintain the spacecraft, conduct orbital science activities, and teleoperate the Mars rovers. Assuming that these two crewmen each serially dedicate 4 hours per day to teleoperation activities (assisted as required by communications satellites), a total of 240 hours of exploration can be accomplished. Additional on-line crew teleoperation time is potentially available if the Phobos exploration crew reduces its stay time at Phobos in favor of supporting the acquisition of additional data from the Mars rovers; i.e., assuming two or more crew members can simultaneously operate from a single control station or assuming there are multiple control stations onboard the mothership.

However, compared to previously successful (though presumably less technically sophisticated) American and Soviet Mars and lunar robotic missions, this is an extremely brief operations period. Therefore, it will be vital that exploration sites be carefully selected through analysis of precursor mission data and synthesis of desired mission objectives, and that Earth operators complete checkout, initial placement, and real-time mission objective "tweaking" activities with the rovers prior to mission crew involvement. The brevity of the operations period may be partially compensated for by beginning the teleoperations prior to Mars orbit insertion during the final weeks-to-months of the cis-Mars coast period. However, designing the rover systems (and training the crew) to respond to ever-changing signal-lag times presents an additional complication to this approach.

**Phobos Exploration.** The expedition to Phobos represents the first opportunity for humans to explore the surface of and assess the operations for exploration of an essentially gravity-free, asteroid-type body. Phobos presents a unique set of environmental characteristics, particularly in terms of its nearly absent gravity, that must be considered in mission and contingency planning so that options can be pre-selected to ensure mission success. Studies were conducted in FY 1988 to obtain information on (1) methods of exploring the Phobos surface under low gravity conditions; and (2) the characteristics of controlled flight in close proximity to the surface. The information, although preliminary, will help define vehicle and equipment requirements.

Phobos has a small gravity force that would keep a motionless body on the surface. However, the potential for leaving the surface for extended periods of time (10-30 minutes) due to inadvertent pushes or bounding off terrain features is high. This seems to indicate a need for anchoring methods to maintain surface contact and to create a stable work platform for sampling.

Flight over Phobos has the benefit of ease of traverse, including the ability to alight "anywhere" and to avoid obstacles. Flight trajectories on the surface of Phobos to be investigated in greater detail in FY 1989 include both short round-trip traverses of less than 2 kilometers and long round-trip traverses of up to 10 kilometers.

### Surface Systems

**Lunar Surface Power.** In the Lunar Observatory Case Study, the ground rule for crew stay time on the surface was one lunar day (two Earth weeks) for both the observatory setup and operations periods. This rule was intended primarily to keep mission objectives and manifests at a level commensurate with reasonably low annual mass to LEO (and, consequently, manageable LEO infrastructure support requirements). However, as the

case study analysis progressed, an option emerged that had potential merit for the observatory setup phase: allow the crew to stay over for one or two lunar night periods in order to have more construction time (and possibly complete construction on one mission). Although this would require more mass to be Earth-launched on the setup missions, it would require fewer Earth launches overall and, consequently, could be significantly more cost-effective.

One important aspect of lunar observatory operations (including the option of crew stay-over) is that of power availability for lunar day and night activities including crew habitation, observatory construction, and instrument operation needs. The crew is assumed to use lander vehicle power for their habitation needs during the emplacement of the baseline solar photovoltaic (PV) observatory power system and the initial set of mission science experiments. At this point, the PV system can begin supplying power for daytime surface activities, continuing construction as well as instrumentation operations. The functioning PV system could also be used during the daytime, as power budgets allowed, to supplement or replace lander power for extended crew habitation needs.

The issue is now: Which energy storage devices are best for use during the ensuing lunar night—by the observatory instrumentation for continued science data return, and by the crew for extended construction and habitation needs? Conventional power systems (rechargeable batteries) are very massive and are not suitable for prolonged use in complementing solar-based power systems. However, advances in rechargeable hydrogen-oxygen fuel cell technology could make storage for the long lunar night feasible.

A primary fuel cell (one which uses supercooled hydrogen and oxygen to produce water and electricity and which is not rechargeable) could be used to extend the crew stay period over one lunar night without incurring an excessive mass penalty for cryogenic storage tanks. However, once used, the fuel cell (and cryogenic storage tanks) must be expended. Multiple stay-overs (and multiple primary fuel cells and storage tanks) would require significant additional mass. Technology advances in the regenerable fuel cell (one which uses gaseous hydrogen and oxygen to make water and electricity, then uses part of the generated power to electrolyze hydrogen and oxygen from the water byproduct for reuse as fuel) could make energy storage for use during the long lunar night feasible: i.e., both fuel cells and fuel storage tanks are reused, thereby reducing the mass penalty for continuing crew and equipment power needs.

This solar PV power system consists of amorphous silicon roll-out arrays to provide initial power. Sun-tracking

fold-out arrays and regenerative fuel cell storage equipment are then deployed/erected. The final stage of construction would consist of connecting the initial arrays to the regenerative fuel cells for nighttime operation. The fold-out PV arrays provide constant daytime operational power to the Lunar Observatory. The complete system can probably be set up within one 14-day stay. A power system with regenerative fuel cell storage capable of supplying the required continuous day/night power is estimated to have a mass in the 7-8 metric ton range. However, once the regenerative fuel cells are operational, extension of the power system construction period into the lunar night is possible.

This year's studies also provided a conceptual design of a nuclear power system. Configurations were selected to enable and/or enhance a lunar base mission. Numerous components and coupling techniques were examined, and recommended options were chosen for safety implications, high performance, low mass, and ease of assembly.

For power levels in excess of 60 kWe, the nuclear reactor exhibits a mass advantage over the solar PV power system, which increases significantly with higher power requirements. As the base expands to include scientific experimentation, rover recharging, and soil processing, a nuclear power system becomes the most viable means of meeting the higher power requirements.

The nuclear power system examined this year consists of a 2,500 kWt SP-100 reactor coupled to eight free-piston Stirling engines. The reactor is identical to the design currently baselined in the SP-100 program, but the Stirling engines replace the thermoelectric power conversion system. Two Stirling engines are held in reserve to provide engine back-up for dependable power generation. The other six engines operate at 91.7 percent of their rated capacity of 150 kWe. The design power level for this system is 825 kWe. The system is modular and can be replicated in increments of 825 kWe to meet higher power requirements.

Excluding the mass of required construction and maintenance equipment, this nuclear power system conceptual design offers the potential for a substantial mass savings over comparable PV/storage power systems. For example, the mass of a 50 kWe solar PV power system with regenerative fuel cell storage for full night capability exceeds the mass of the entire 825 kWe nuclear power plant. The nuclear system also enables continuous day and night operations without the need for energy storage.

The "bottom line" is that the integrated power system (PV augmented by either primary and/or regenerable fuel cells, or nuclear power) must have a power genera-

tion and storage capability sufficient to meet the ongoing setup (20-40 kWe) and operational (50-100 kWe) power needs of the lunar observatory and must also meet the overall case study objective of minimizing annual IMLEO during the operational period. Further studies are required to converge upon the optimum mix of power generation and storage devices with mission strategies and observatory objectives.

**Advanced Life Support Systems.** A spacecraft or planetary surface habitat crew life support system (LSS) provides the following basic functions: atmosphere revitalization, temperature and humidity control, food supply, personal hygiene, water management, and waste management. Each case study under consideration requires reliable and efficient LSS technology, for the health and well-being of the mission crew as well as for reduction of mission IMLEO requirements. However, the more complex the mission strategy, the more highly sophisticated must be the LSS.

For the Lunar Observatory Case Study, the piloted space transfer vehicle can have an LSS that is essentially open-loop (food, water, and breathing air supplied as IMLEO with limited onboard water recovery, air revitalization, and food processing.) This system could be developed, in large measure, using existing shuttle LSS physical/chemical technology. On the other hand, the LSS technology required to support the crew during the "everyday" extravehicular activity (EVA) operations performed to construct and maintain the observatory requires significant enhancement from the "current" technology as used to support the Apollo missions, especially with regards to overall system mass and serviceability.

Consequently, recent lunar EVA studies were analyzed and top-level requirements for the lunar EVA system were generated. Basic requirements for the LSS are that it will need to be both lightweight enough and small enough in volume to allow for easy, convenient EVA in the lunar gravity field, while supporting 6-8 hours of EVA per day. Further, post-EVA servicing for reuse must be accomplished within the logistics allowance (spares availability, dedicated crew time, etc) for the lunar base. The space suit assembly must be flexible enough to allow unaided resumption of footing after a fall, must allow exceptional hand-dexterity to permit extended (multiple-day/week) performance of EVA, and must tolerate the lunar dust environment. Trade studies were identified in these two areas and in the additional areas of support equipment and support vehicles which, when performed, will allow more detailed definition of lunar EVA requirements.

Mars expeditionary class vehicles, on the other hand, will clearly require a more robust LSS technology that is operable in both the deep-space and nonvacuum plane-

tary surface environments, is reliable over the length of the mission (14 months or more) and is "closed" (recovers and reuses or regenerates consumables needed for drinking, bathing, breathing, etc.) to the greatest extent practical given the desired mission launch year, constraints on vehicle mass and volume, and the status of empirically proven technology. It is anticipated that the partially-closed, physical/chemical Space Station Freedom LSS technology, when successfully demonstrated, will suffice for this class of exploration vehicle. However, to support EVA in the one-third gravity Mars surface environment, advanced technology suit systems must be developed that may be significantly different from their lunar counterparts. Subsequent studies will examine Mars EVA requirements in detail.

Evolutionary-class missions place much more constraining demands on the associated LSS: not only on the space transfer vehicle(s) during the months-long transit periods, but also upon an evolving surface systems infrastructure (including increasingly robust EVA support systems) which must support a number of people for periods of up to two years or more without benefit of frequent Earth resupply. A space transfer vehicle and surface systems LSS technology base characterized by a high degree of closure, extremely high reliability, ease of maintenance, increased automation, and independence from terrestrial resources will be required if missions of this type are to be successful. Continuing research should include a variety of LSS technologies including advanced physical/chemical and biological.

### **Cost Understanding**

This special study was conducted to update the assumptions and art of estimating costs of major initiatives that are at the concept stage, with implementation far into the future, using experience and techniques that are difficult to predict with present information. In traditional cost estimating models, it is assumed that historical trends and methods of doing business will continue in the future. This cost understanding analysis takes a fresh look at the analytical, political and social "science" of cost estimating, and attempts to isolate the programmatic features that influence cost. A "tailored" method must be developed to include programmatic and specific NASA assumptions on the environment in which initiatives will be developed.

Some of the major program features that impact mission costs are: the way in which hardware is designed, developed, and built; program management philosophy; and expectations of rate of technology development. After a preliminary assessment, the following recommended assumptions for incorporation into a tailored cost model can be made.

### **Hardware:**

- Acquisition cost realism and unit production cost are significant design requirements.
- Product improvements and maximum use of proven components and subsystems (especially commercial items) should be planned.
- A continuous alternative should be available.
- Use mass production as much as possible.
- Minimize functional complexity of individual hardware elements.
- Seek commonality among hardware elements.
- Design hardware elements with substantial performance margins.

### **Program Management:**

- Design short, stable schedules for development and production.
- Use experienced, small staffs, with clear channels of command and limited reporting.
- Establish effective communication with users for cost/performance trade-offs.
- Seek early development phase funding for production and support considerations.

### **Technology:**

- Technology should be pushed forward only at reasonable rates as determined by the recognized technology manager.

# Science Opportunities in Human Exploration Missions

As NASA is exploring potential programs to fulfill the national policy guidelines of expanding human presence beyond Earth orbit, it is important to consider what that means in terms of advancing scientific knowledge. Although science objectives may not represent the principal motivation for undertaking human expansion, they will generate many of the most visible accomplishments as the missions are carried out. Therefore, in order to maximize the scientific accomplishments of a program of human expansion, a science strategy should be developed from the beginning of that program.

The opportunities (or requirements) for science in the proposed OEXP case studies have been developed in an ad hoc manner in FY 1988. The scientific information available has been derived through inputs from individual scientists, a few workshops, and the literature. Furthermore, this content has not undergone the scrutiny of a scientific oversight function. Thus, the work performed in the past year does not constitute a science strategy, but has looked to incorporate some ideas on science objectives into the engineering analysis.

The general science and exploration objectives for the OEXP case studies are:

- To study the planetary bodies to understand their origin, history, and current state, and to understand their relation to Earth and the origin of the solar system.
- To seek evidence for the origin and evolution of living organisms through the identification of environments in which life could have existed, or through the identification of physical or chemical remains.
- To conduct studies of the universe that can be uniquely or effectively undertaken utilizing the new environments that would be accessible in the human exploration program.
- To utilize these newly accessible environments to conduct important studies in other fields of science (e.g., high vacuum, very low gravity).
- To understand the abilities and limitations of human beings for extended duration spaceflight.
- To determine the feasibility and utility of establishing permanent human outposts on the surfaces of other planets.
- To investigate the potential resources available in near-Earth space.

The special capabilities of humans as observers, integrators, and interpreters provide the greatest leverage in performing science-related tasks such as: the exploration of new environments, searching for subtle or uncommon features, modifying experiments or studies based upon new real-time information, and maintaining and repairing mechanical devices.

For the exploration missions themselves, three general types of experiments/investigations can be considered:

- Investigations that make unique use of the capabilities of people functioning in the space environment. Two examples are: direct exploration, where the human intellect can contribute to new observations and react to the unexpected; and the local teleoperation of machines by humans.
- Investigations that take advantage of the opportunity to emplace scientific payloads in new places. For example, the operations to transfer humans to the Moon and Mars can be used to transfer major scientific payloads as well.
- Opportunities that may come about as ancillary products of non-scientific activities. For example, lunar or Phobos mining activities could provide substantial new opportunities for geological investigations of those areas.

The case studies developed in FY 1988 offer the following potential opportunities in lunar exploration: (1) establishing scientific observatories and exploration base camps; (2) developing capabilities to produce resources for both propellants and life support; and (3) exploring the potential uses of the Moon as a testbed for the establishment of self-supporting human outposts on other planets. In addition, many unanswered geological questions about the origin and history of the Moon can and will be addressed by human explorers.

The lunar surface is an attractive place to establish major astronomical facilities, because of its environmental qualities: high vacuum, stable base, extensive available surface, mitigation of structural problems due to the one-sixth gravity environment, slow rotation allowing long observation times, and the far side permanently shielded

from the Earth.

The current understanding of Phobos and Deimos is meager. The structural complexity and the apparently primitive nature of the surface materials suggest that direct human exploration will be required to answer the main questions of origin and history. A significant objective of Phobos exploration is to establish its characteristics well enough to evaluate whether water and materials useful as rocket propellants are present in sufficient quantities. Samples of Phobos regolith will need to be returned to Earth so that specific extraction techniques can be designed.

The exploration of Mars in a reconnaissance mode can be carried out to a large extent by robotic devices. At the current state of understanding about the Martian environment, it is difficult to speculate on the specific scientific objectives of a human expedition. Much will be

learned in the next ten years to focus the objectives and hazards of human exploration of Mars.

In a general sense, there will be problems or issues identified by robotic missions that will remain too complex or subtle to be resolved by robotic exploration. For example, a highly important scientific objective of Mars exploration is the search for evidence of existing or ancient life. Although conclusive evidence could possibly be obtained by robotic missions, it is more probable that the evidence is subtle enough and scarce enough that human exploration will be necessary to make the appropriate interpretations to resolve the issue.

The scientific rationale presented here is an initial assessment, which needs to be developed in greater depth, by NASA and the scientific community, to provide guidance to human exploration mission development.

# Comparative Analysis of FY 1988 Case Studies

The primary objective for FY 1988 was to develop a set of case studies with a consistent methodology and to a uniform level of detail so that diverse exploration strategies (expeditions, science outpost, and evolution) could be compared and contrasted. The purpose of this effort was to determine the major factors that drive results of current and future case studies in terms of scale, complexity, feasibility, and benefits. Broad trade studies and special assessments were conducted to identify specific, innovative techniques and technologies that could be of significant benefit to mission performance. For example, the scope and potential of various mission designs can realize a significant advantage by the use of advanced technologies; the assessments performed in this year's study cycle sought to determine the degree to which this is true. Another high-level factor is the cost and complexity versus the benefit of using a node in low-Earth orbit for assembly activities. Case studies were examined to explore these extremes.

To develop a strong knowledge base of exploration pathway sensitivities, the case studies were selected to encompass a broad range of objectives, requirements, and

capabilities. The mission strategies range from one-mission, expeditionary approaches to a long-term evolutionary approach. The technology needs are deliberately paced to include those that will be available in the near term, in addition to assuming the use of highly sophisticated developments. In order to drive out an understanding of Earth-to-orbit delivery capability and need, the requirement for the amount of mass that must be lifted to low-Earth orbit ranges from 250 metric tons in the peak year for the Lunar Observatory, all the way to seven times as much mass, 1,770 metric tons, in the peak year for the Mars Expeditions.

The selected group of studies lands human explorers on the surface of another world any time from 2003 to 2014, with planetary surface stay times from as little as 14 days to almost two years. Gravitational conditions generate a unique range of requirements: on Phobos, the gravity is nearly zero; on the Moon, it is one-sixth that of Earth; on Mars, the gravity is one-third that of Earth; and during transit it is zero. The studies also cover a wide variety of trajectory profiles, number and frequency of flights, and mission duration.

Table 1. CASE STUDY SHAPING PARAMETERS

<b>Parameters</b>	<b>Earth-to-Orbit Transportation</b>	<b>Low-Earth Orbit Assembly</b>	<b>Technology</b>	<b>Other</b>
<b>Case Studies</b>				
<b><u>Expeditions Strategy</u></b>				
<b>Human Expedition to Phobos</b>	Large mass per launch	No assembly node	Use then-existing technology	Earliest mission
<b>Human Expeditions to Mars</b>	Large mass per year	Significant assembly at node each mission	Moderate increase in technology	Significant precursors
<b><u>Science Outpost Strategy</u></b>				
<b>Lunar Observatory</b>	Minimum mass per year	Minimum assembly at node each year	Moderate increase in technology	High science return
<b><u>Evolutionary Strategy</u></b>				
<b>Lunar Outpost to Early Mars Evolution</b>	Approximately constant mass per year	Moderate assembly at node each year	Advanced technology	Extraterrestrial resource usage

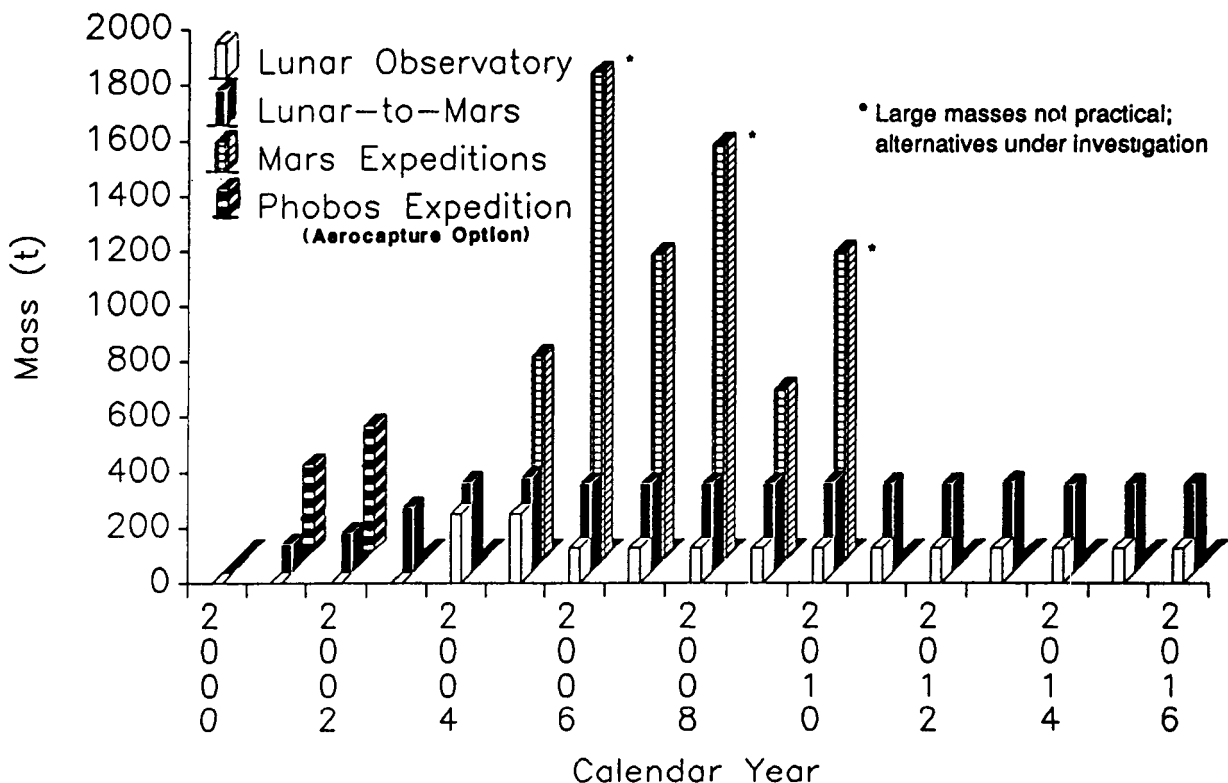


Figure 12.- Case studies mass summary—annual mass to LEO requirement

As a result of this process of developing a broad spectrum of strategies and approaches, a fairly extensive base of information has been developed that has enabled some new insights to be gained. The "lessons learned" over the past year are described below; they will be applied, in a continuing process of study, to the redirection and definition of future work. One overriding lesson has become very clear: this Nation must begin, now, to make the near-term investments that will make human exploration at the turn of the century possible.

The key parameters that shape case studies are: (1) Earth-to-orbit transportation; (2) low-Earth orbit assembly and operations; (3) technology, including concepts of utilizing extraterrestrial resources; and (4) other factors that are unique to each case. A summary of these case study shaping parameters is shown in Table 1. As each of these parameters is applied to each case, an overall comparison of the full set of case studies and associated trades can be made.

#### Earth-to-Orbit Transportation

A dependable, high performance Earth-to-orbit (ETO) transportation capability is of fundamental importance to the success of any exploration initiative. Whether

derived from current National Space Transportation System booster components or developed as a separate heavy-lift launch vehicle, new capabilities will be required to enable timely delivery of massive space transfer vehicles, propellant, mission payload components, and support hardware to low Earth orbit for assembly and checkout. For instance, the Human Expedition to Phobos will require a large initial mass to be lifted to orbit, especially since this particular case is constrained to minimize low-Earth orbit assembly. On the other hand, the Mars expeditions could be accomplished with smaller ETO vehicles, since assembly in orbit is not constrained by the case study ground rules. However, issues related to ETO launch frequency and available accommodations at the LEO node then become important for Case Study 2. Figure 12 illustrates the annual mass to LEO delivery requirements. This mass flow is of fundamental importance, since it directly affects the nature of the required ETO delivery system and Earth-orbital support facilities; furthermore, it is a first-order indicator of total cost. In general, the expeditionary approach is characterized by very large peaks in mass, corresponding to the year chosen for launch. In contrast, both the Lunar Observatory and the Lunar Outpost to Early Mars Evolution cases are characterized by steady rates of much lower magnitude.



Because of the lack of maturity projected to exist in on-orbit assembly operations at the beginning of the next century, the earlier the mission (i.e., the Phobos case study), the stronger the case for minimizing such activities. This fact supports the development of more capable ETO launch vehicles, in order to lift larger, but fewer, components to orbit. Heavy-lift vehicles currently under study assume a mass-to-LEO capability of about 91 metric tons. With this performance, the baseline Phobos case requires as many as 20 to 30 separate launches. In addition to factors of cost and availability of ETO vehicles, the impacts on ground logistics for multiple flights per year are extensive. A major decision that this nation faces is whether to invest in developing a heavy-lift vehicle that is at least twice as capable as those currently under study, to invest instead in a smaller lift capacity with higher flight rates and develop an extensive capability for in-space assembly of large structures, or to effect a compromise between heavy-lift capacity and level of assembly in LEO. The issue of ETO capability cannot be considered separately from the next functional area, LEO assembly and operations.

### **Low-Earth Orbit Assembly and Operations**

The choice of investment and mission strategies that affect LEO activities is a function of many interrelated variables. As presented in the previous section, it is recognized that there is a trade between on-orbit assembly and ETO capability. In general, it is expected that the development costs of ETO transportation increase as the requirement for lift capability increases. On the other hand, as ETO lift capability increases, the expected trend is for the number of required on-orbit operations (and assumed costs) to decrease. This therefore implies that cost-optimum parameters exist that need to be identified.

Many of these issues were addressed in a cursory manner by trade studies and assessments in FY 1988, and these analyses will continue in more depth in FY 1989. However, some observations can be made, based on the preliminary results. Given our current experience in space assembly operations, it is extremely difficult to project forward to the level of operations required for these case studies. Obviously, lessons learned while we design Space Station Freedom will be important. Many of the assembly issues encountered during Freedom's ongoing design and development activity are common to the case studies as well, and the results may be applicable. Space Station Freedom's assembly planning has already experienced constraints imposed by the ETO systems (Shuttle) and by crew (EVA time).

An important lesson learned from the Space Station Freedom experience is that the ETO support functions must commit to transportation performance stability in terms of agreed-to ETO performance. Degradation in

delivered vehicle performance from concept definition to flight status could have potentially significant impacts on ongoing activities, since the development of the space transfer vehicles would begin prior to ETO vehicle flight readiness.

Equally important will be the level of automation and robotic technology available at the time to assist with, or perhaps perform all of, the assembly operations. Our special assessments and prerequisite technology programs indicate that complex, detailed assembly operations will not be ready for robotic application in time to support our earlier (i.e., 2000) need dates. Thus, our current ground-based knowledge argues for minimizing and/or simplifying space assembly operations for the early missions, e.g., the Human Expedition to Phobos. However, some of the other cases, such as the Lunar Outpost to Early Mars Evolution study, envision advanced, reusable vehicles and the use of lunar liquid oxygen, which implies a high degree of readiness for in-space operations technologies only a few years later. Since this particular case evolves over a longer period of time, it can and must be integrated with development programs. This is consistent with the forward-thinking philosophy employed in the development of the evolutionary case.

To reduce the LEO mass to more manageable levels, an aerobraked option was analyzed for the Phobos mission. This option resulted in about one-half the LEO mass of the baseline case. It was intended to reduce the LEO mass to the point where major components (i.e., complete cargo or piloted vehicles) could be assembled on the ground and launched on a very heavy-lift or "magnum" launch vehicle. Even so, this mass is still large enough to suggest that some assembly in LEO is a better approach than a single magnum ETO launcher. Reducing the crew size for the Phobos mission further reduces the mass in LEO requirement and the subsequent ETO launches and space assembly operations.

Integrating the launch vehicle and spacecraft to synergize the use of upper stages is one approach to minimizing assembly operations that warrants close scrutiny. Other innovative approaches, such as advanced space propulsion (e.g., nuclear thermal rockets), may be necessary to undertake a major exploration program without a LEO node. Further study is required to understand, with any certainty, whether or not this mission can be accommodated without any LEO support infrastructure.

At the other extreme of on-orbit assembly needs are the Mars expeditions and Lunar Outpost to Early Mars Evolution; these case studies have been structured to permit a significant amount of activity in LEO, and, therefore, have resulted in very challenging node support and operations scenarios. To define the operations

for in-space assembly and vehicle processing for these cases, the natural tendency has been to attempt to understand our current experience in ground processing, and extrapolate it to orbital operations. However, current ground processing flows for space vehicles represent a resource and time requirement that becomes unrealistic to impose upon on-orbit operations. New ways to process space vehicles that are assembled/mated on-orbit will need to be developed in order to reduce the LEO operations work load and make these cases viable.

The resolution to this challenge most likely will be a combination of revising the vehicle design, eliminating processing functions, maximizing vehicle ground processing of resource-intensive tasks, incorporating automation and robotics and other strategies to enhance productivity and capability, and reducing the number of on-orbit operations. This strategy will require both a "bottom-up" and a "top-down" approach for FY 1989. The bottom-up approach is one that begins with the current vehicle ground processing flows. Each function currently being performed needs to be accounted for in some manner (e.g., not required, incorporated into design, integrated with other functions, etc.) as do new ones identified for the reference vehicles. The top-down approach is to establish an assembly resource allocation to be levied as a requirement for the integration agents to meet. Results from both methods would then be used for convergence of requirements.

For missions to Mars and Phobos with short travel times (i.e., split/sprint or opposition), using aerocapture as the means of Mars orbit insertion translates to a savings of approximately 50% back at initial LEO requires fewer ETO launches and has the potential to alleviate requirements for on-orbit assembly. However, the technique of "assembling" the large aerobrake in LEO is not well understood, and it cannot be unequivocally stated at this time that a LEO node would not still be required in order to assemble the aerobrake. Alternative crew module aerobrake designs that could be smaller, such as non-reusable ablators, could alleviate this problem, as could the use of nuclear thermal rockets. The advantages of using aerobraking are much less for trajectories with longer trip times; therefore, a trade exists between mission duration (reliability, human performance) and LEO assembly capability.

### **Impacts of Using Advanced Technology and Extraterrestrial Resources**

The use of one or more key advanced technologies can cause a significant reduction in Initial Mass to LEO (IMLEO) requirements. As stated earlier, the use of aerocapture for orbit insertion at Mars and Earth can reduce the IMLEO requirements by one-half over the use of standard chemical propulsion for orbit insertion for

split/sprint missions to Mars and Phobos. Advanced propulsion techniques such as Nuclear Thermal Rockets can reduce IMLEO for the Phobos Expedition by one-half and the Mars Expeditions by one-third. Using an electric, low-thrust cargo vehicle in the Lunar Outpost to Early Mars Evolution case can potentially reduce IMLEO by one-third over a standard chemically propelled vehicle. Also, advanced nuclear thermal rocket technology for the piloted vehicle offers the potential for simultaneously reducing trip time, mass to LEO, and the logistical complexity of the evolutionary case study. For the Lunar Observatory, advanced energy storage could extend crew stay-time through the lunar night, and could also eliminate an Earth launch.

The use of extraterrestrial propellant is a potentially high-leverage technology, and it was incorporated into the Lunar Outpost to Early Mars Evolution case study. In this case, the use of propellant from the Moon and Phobos (coupled with the use of electric propulsion on the cargo vehicle) can reduce the IMLEO by more than one-third compared to the use of all Earth-based propellants.

The special assessment study on power showed a substantial mass advantage for nuclear power technology when compared to photovoltaic/regenerative fuel cell technology. When this mass advantage is folded into the total integrated lunar surface systems, the end result is a total case study mass reduction at LEO of one-half to three-fourths, depending on mission configuration.

These are only a few examples of how advanced technologies are enabling for some areas and enhancing for others. The objective is to stimulate the development of technologies for the case studies to build a solid technology base from which NASA can select to support a variety of missions. This technological maturity will allow additional manned missions to other planets.

The problem that must be addressed is that different technologies are often competitive with respect to developmental funding support. The question to be answered is which is more advantageous to pursue, from the standpoint of development cost and risk. An example would be that aerospace plane materials technologies and systems designed for the Advanced Launch System program could reduce LEO access costs to the point where extraterrestrial propellants would not be competitive with Earth-delivered propellants in LEO. However, which technology development has a greater probability of becoming a reality in the planned need time-frame, which has less operations risk, and which has the lower development costs? Related issues must be better understood through future case studies and trades.

The use of advanced technologies in a program carries with it an element of risk if the technology is developed

in series with its intended use in the program. To alleviate schedule impacts, development of enabling technologies must be initiated well in advance of their required use. Ideally, technology should be at a technology readiness level five or six (laboratory-demonstrated or integrated into a hardware subsystem) at the start of Phase C/D. The technology readiness level at the start of Phase C/D will depend on the perceived risk of the non-availability of the technology to support the mission; the higher the risk, the higher the technology level required.

Alternative technologies must be available for each case study or the mission may be in jeopardy. The alternative technology may mandate that more mass be required to support the mission; for example, using propulsive orbit entry as opposed to aerocapture will impose a mass penalty. For all the critical technologies, it must be determined whether an alternative exists and what the impact will be on the mission if that alternative is used. By allowing for the development of the technologies with proper funding and scheduling, the use of alternatives can be minimized.

The technology development programs were integrated with the case study programs, and where these programs were incompatible, alternative solutions were chosen wherever possible and practical. This was not possible in all cases and outstanding incompatibilities remain in three areas: (1) propellant transfer, (2) nuclear electric propulsion, and (3) Mars-to-Earth aerobraking. Also, some technology areas are not addressed currently in Project Pathfinder, and thus some additional work will need to be accomplished. A majority of technologies are common across most of the case studies, which indicates that by developing a core set of technologies it is possible to preserve the decision option for a number of missions.

#### Other Factors

In addition to the parameters that pertain to all case studies, each also holds a particular emphasis that must be considered in the overall planning strategy. These emphases are strictly dependent on the case study scenario itself, and also on the basic strategy that is selected for exploration.

For example, if the major motivation to be stressed is to achieve the earliest and first human voyage to another planetary body, then the Human Expedition to Phobos, which could arrive as early as 2003, becomes a most attractive option. If, however, the strategic emphasis is on the facilitation of opportunities for lunar geophysical and cosmic astrophysical research, the Lunar Observatory Case Study could be considered attractive. The Human Expeditions to Mars have substantial precursor requirements, both in terms of robotic missions to characterize the planetary conditions, and life sciences research to determine the effects on human beings of long-term exposure to the environment of space. And the Lunar Outpost to Early Mars Evolution case study explores and exploits the use of many new technologies, including those that mine and refine resources on the Moon or Phobos.

Clearly, the parameters derived from the studies conducted in FY 1988 define a complex and interconnected situation. Many elements must be identified, assessed, planned for, and developed in parallel to enable the success of any mission. At the very heart of case study development is Earth-to-orbit transportation and the need for an ambitious launch schedule and a stable of vehicles that includes the Space Shuttle, a heavy-lift launch vehicle, expendables, and other advanced systems. Also critical to each case study is the availability of Space Station Freedom or another platform in low-Earth orbit for assembly, in addition to a heavy-duty LEO space "tug". The technology development schedules that are assumed impact all case studies, and each choice favors a particular exploration strategy.

Table 2 provides a summary comparison of key characteristics for the case studies. By studying the data in this figure, such as: arrival date, initial mass, mass delivered to final destination, number of crew members, etc., a relative assessment of the complexity and capability of all the case studies emerges.

TABLE 2 - SUMMARY OF CASE STUDY CHARACTERISTICS

SCENARIO DESCRIPTOR	LUNAR OUTPOST-TO-EARLY MARS EVOLUTION				
	HUMAN EXPEDITION TO PHOBOS	HUMAN EXPEDITIONS TO MARS	LUNAR OBSERVATORY	LUNAR PORTION	MARS PORTION
o TRANSPORTATION					
- TRAJECTORY PROFILE	Cargo: min. energy Crew: sprint	Cargo: min. energy Crew: sprint	Translunar	Cargo: low thrust	Cargo: low thrust
- NUMBER OF FLIGHTS	1 Cargo, 1 Crew	3 Cargo, 3 Crew	2 Cargo, 2 Crew (set-up); 1 Crew flt per year thereafter	Crew: translunar continuing LEO/LLO & LLO/LS shuttles	Crew: near fuel min 1 Cargo, 3 Crew
o CREW SIZE	4 (2 to Phobos surface)	8 (4 to Mars surface)	4	8	8 (8 to Mars surface)
o TOTAL CREW TRIP TIME	440 days	440, 440, 500 days	≤ 20 days	≤ 1 year	35 to 45 mos.
o SURFACE STAY TIME	30 days in Mars orbit 20 days at Phobos	30 days in Mars orbit 20 days on surface	< 14 days on surface (daylight only)	≤ 1 year	1-2 years
o EVA's (6 hours per EVA; two crew per EVA)	4~ EVA's at Phobos	4 EVA's at moons 10 EVA's at Mars 10-km unpress. rover traverses	12 EVA's 10-km unpress. rover traverses	EVA's as required 10-km unpress. rover traverse	EVA's as required 10-km unpress. rover traverse and 100-km press. rover traverse
o MASS TO LEO PEAK YEAR	Peak: 453 t @ 2002 Aerocapture option	Peak: 1770 t @ 2006	Peak: 250 t @ 2004 and 2005	Peak: 345 t @ 2005	
o PROPELLANT MASS (t)	Cargo veh: 234 Piloted veh: 318	Cargo veh: 1796 Piloted veh: 3363	Cargo veh: 87 Piloted veh: 96	Total: 1660 (all flights, lunar & Mars)	
o USER ALLOCATION (t)					
- ORBITAL	~2 (includes Phobos expts)	12.5, 12.5, 6	7	3.3	12
- SURFACE	7 t Total: 2 teleop explorers on Mars	15, 15, 15	17.5 / Cargo flt. 6.5 / Crew flt.	(cumulative) 112	Mars - 58 Phobos - 10
o PROPELLANT PRODUCTION	n/a	n/a	n/a	Four LLOX plants (40 t each)	Phobos prop. plant (86 t)
o YEAR - 1ST HUMANS TO SURFACE	2003	2007	2004	2004	2014

# Program Integration Approach

Human exploration strategies are intimately connected to the plans and schedules of all the NASA program offices. The success of such efforts depends on the integration of exploration plans with those of programs involving transportation, life sciences research, scientific precursor missions, Space Station Freedom, technology, and communications and data tracking.

## Earth-to-Orbit Transportation

All human exploration missions will require substantial mass to low-Earth orbit; clearly, our present launch capability must be augmented. To meet the cargo transport requirements for the Mars expedition, the Lunar Observatory, or the evolutionary case studies, launch systems with an annual capacity to deliver multimillion-pound payloads are required. These systems must include vehicles with an individual capability of at least 91 metric tons (200,000 pounds). This assumes that a significant amount of on-orbit assembly is possible, which must be validated with further study. To minimize on-orbit assembly, a vehicle with even greater capacity is required.

The development of the heavy-lift launch vehicle, with capability to deliver up to 91 metric tons, must stay on track and become operational by approximately 2000. In the interim, to support prerequisite technology demonstration missions and science precursor programs, the Shuttle-C (Shuttle cargo vehicle) or an equivalent should be operational by the mid-to-late 1990s. Personnel transport solutions are still under study, but some augmentation will probably be needed. The exact degree to which enhancement is required depends on the amount of on-orbit assembly and vehicle processing that is performed by the crew, but in the near term, various methods of increasing our current capability must be examined. Personnel transport and orbital housing could present a major issue if more than 20 crew members are required in addition to the dedicated Space Station Freedom personnel.

## Life Sciences Research

To permit safe, productive, long stays in space, the life sciences research program to assess, understand, and alleviate the effects of long-duration spaceflight on the human physiological and psychological condition is of primary importance. In general, missions to the Moon are far less demanding of prerequisite life sciences needs, primarily because of short flights and stay times, and the ability to use the Moon as a "real-time" life sciences

laboratory, as in the evolutionary scenario (Case Study 4). Analysis indicates that with investment in the life sciences base research program, combined with research defined in the proposed Life Sciences Strategic Plan, Case Study 3 and the lunar portion of Case Study 4 could be initiated without additional precursor human research. To support direct expeditions to Mars (Case Studies 1 and 2), additional research programs must be planned in areas of artificial gravity and closed loop life support systems. Some of the life sciences research for the Mars portion of Case Study 4 will be conducted in the Moon's one-sixth gravity environment during the lunar portion of this case.

Also, for direct expeditions to the Mars system, a very significant driver in terms of both vehicle design and crew capability is the long-term gravity environment that can be safely tolerated by the crew. There is currently substantial uncertainty in the assumed success of the zero-gravity countermeasure program for long-duration spaceflight. Thus, an intensive artificial-gravity research program pursued in parallel with the zero-gravity countermeasures program is a high-priority need. Research investments must be made immediately to determine whether an artificial-gravity or zero-gravity environment is required. This information must be available by 1998 to maintain a first-decade landing schedule; therefore, this research should begin no later than FY 1990. Maintaining cooperation with the U.S.S.R. in life sciences research would be most valuable, as this can give early indications of the zero-gravity/countermeasure program's probability of success.

Since this issue is fundamental to NASA's ability to execute any of these exploration missions, it is absolutely critical that an in-depth understanding of the integrated programs and program interactions be developed early. Research needs to focus on developing zero-gravity and artificial-gravity strategies (life sciences programs as well as vehicle design) that maximize the ability to respond to all potential outcomes and minimize impacts to vehicle and mission design. A sample of the type of integrated strategy needed is offered in Figure 13.

## Scientific Precursor Missions

The case studies mandate a varying number and scope of robotic precursors. Such missions are required to define the environment in which spacecraft and crew must function, by acquiring valuable scientific and engineering data. These missions also serve as technology and engineering demonstrations for such capabilities as

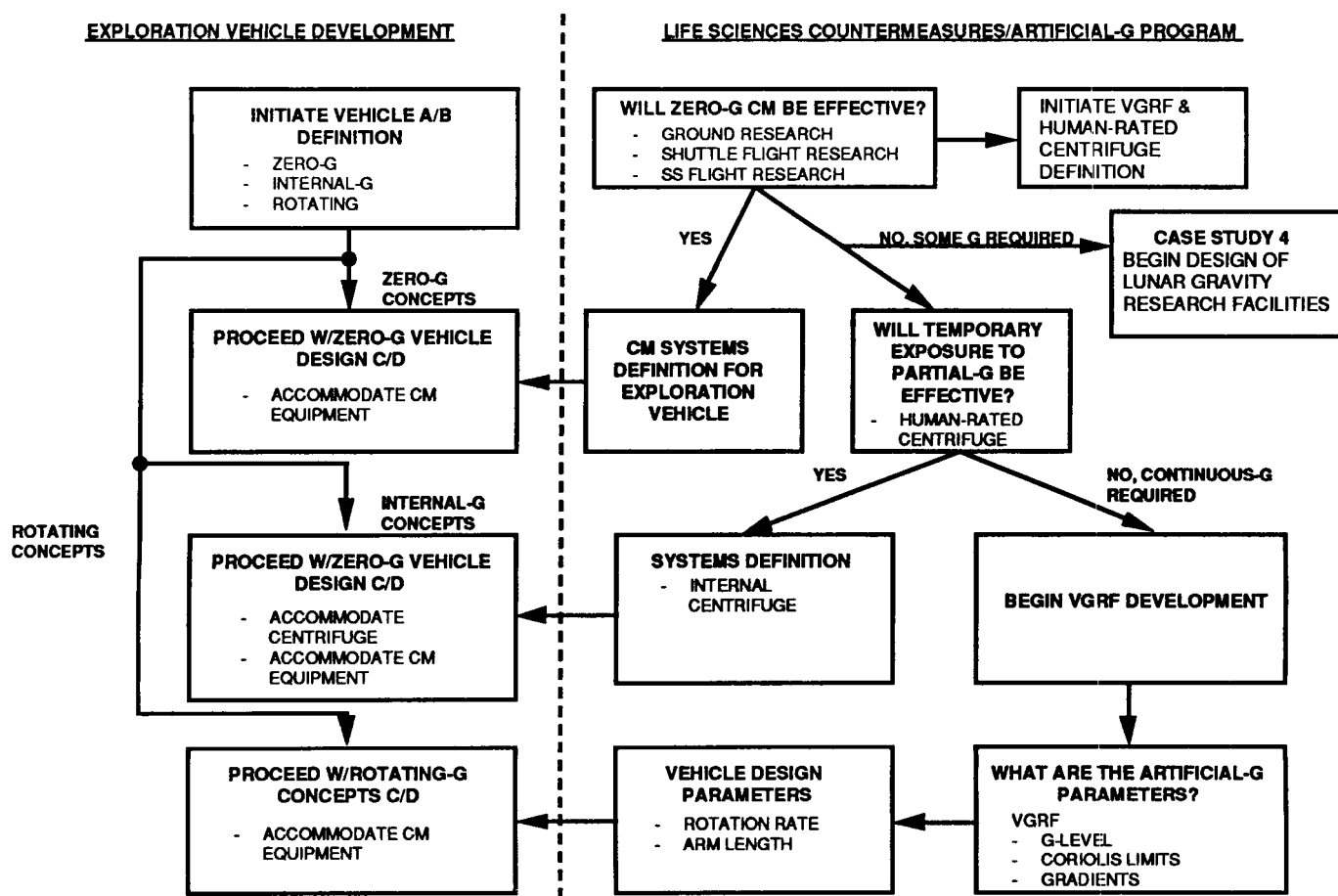


Figure 13.-Typical composite strategy for life sciences research & exploration vehicle development

landing accuracy, aerocapture at Mars and Earth, surface mobility, and autonomous rendezvous and docking. Additionally, for the evolutionary case, sample return from the Martian moons is necessary to plan propellant extraction and processing. Keeping such missions as the Mars Observer, Lunar Observer, and Mars Rover/Sample Return on schedule will provide much of the precursor data, demonstrate incremental achievement, and serve to provide important interim milestones in a very long program. An added benefit is that building on the tradition of international cooperation through jointly conducted robotic space science missions can serve as a foundation of near-term experience toward potential cooperation involving longer-term human exploration ventures.

#### Space Station Freedom

As a base to gain long-duration operations experience, to conduct life sciences research, and to function as a testbed to demonstrate technology, Space Station Freedom's contributions to human exploration of the solar system are monumental. Bringing these capabilities on line

within the current planned schedule will do much to protect our long-term options. Space Station Freedom will most likely serve as a transportation depot; therefore, it is certainly not too early to begin now to define and develop the evolutionary requirements for Freedom. If Space Station Freedom does become the LEO transportation node, the possibility of the on-orbit assembly, staging, and launch operations consuming all of Freedom's resources for extended periods of time must be clearly understood. The scale of these requirements will be driven in large measure by whether the initial destination is the Moon or Mars. Therefore, in order to have the appropriate capabilities in place by the time they are needed, a pathway decision in 1991 or 1992 is important. Space Station Freedom may also play a role in the development of artificial-gravity facilities; the life sciences research mentioned above is needed in 1990 to determine this. At this time, the key considerations are to begin to define reference evolution configurations consistent with our exploration case study requirements, and to develop the advanced technology and program planning that ensures readiness to enhance Space Station Freedom's capabilities at the turn of the century.

## Technology

Key to the near-term investment strategy is to refine and focus the development of technologies required for human exploration through the Pathfinder program, which is pushing advanced technology in the areas of surface exploration, in-space operations, propulsion, nuclear power systems, aerobraking, automation and robotics, humans-in-space, space transfer vehicles, telecommunications, navigation, information management, and many others. Because the period between study initiation and actual mission application can run from eight to twelve years, it is imperative that the commitment to this advanced technology endeavor be sustained. It is also important that, as OEXP exploration studies mature, Pathfinder program research is focused on areas that directly feed into the OEXP plans. In order to contribute to eventual mission design, the Pathfinder technologies must achieve the necessary degree of readiness by the mid-1990s. Funding levels currently planned cannot meet case study requirements, and augmentations (or case study schedule adjustments) are necessary.

In addition to enhancements, certain technologies will require major ground or flight demonstrations as part of the program development process. These include: aerobraking demonstrations beyond the Civilian Space Technology Initiative's Aerodynamic Flight Experiment, cryogenic fluid handling in space, closed ecological life support systems, fractional-gravity spacecraft prototypes, and nuclear power systems.

## Communications and Data Tracking

Telecommunications, navigation, and information management (TNIM) capabilities will require upgrading to support the OEXP human exploration initiatives. There exist a number of options for the architecture of such support systems. The choice of options to pursue will depend upon a number of factors, including the selected exploration scenario and its mission needs, the overall cost-effectiveness of the resulting architecture, NASA life-cycle costs, and the support needs of current unmanned NASA and international-cooperative missions at remote bodies. A final decision on the human exploration strategy with which to proceed is planned for early 1990s; therefore, all candidate support options must be identified and analyzed early and the implications of each option must be understood for each exploration case study.

Our case study approach has demonstrated much of what is needed to accomplish missions to the Moon and Mars. Much detailed research and investment are required during the next 10 years to provide the necessary foundation to enable human exploration in the first decade of the upcoming new century.

# Conclusions and Opportunities

As a result of this process of developing a broad spectrum of strategies and approaches, a fairly extensive base of information has been developed that has enabled some new insights to be gained. One key finding from this year's studies is that the strategies and approaches employed in some case studies were good choices, and in other case studies were bad choices. For example, for the Mars Expeditions, the choice of mission profile, transfer vehicle and surface habitat mass and volume, and propulsion system, etc., drove the mass in LEO requirement to values that are prohibitive. While the scenario employed for the Mars Expeditions turned out to be a bad choice, having that result to add to the base of information is important. The "lessons learned" over the past year will be applied, in a continuing process of study, to the redirection and definition of future work. Some key insights into the human initiatives activities and broad issues that need addressing in future studies are discussed below.

## New Insights

**Nuclear Power.** Nuclear power concepts for both NEP and planetary surface applications need further definition and study. Case Study 4, for example, assumes a NEP Cargo Vehicle with an initial power level of 5 megawatts and specific mass levels of 5 to 10 kg/kWe for both lunar and Mars sorties. At this time, the feasibility of such multi-megawatt, lightweight nuclear power sources is an outstanding issue. Studies and ground-based system tests must be initiated to validate the electric cargo vehicle concept for the evolutionary case.

The FY 1988 study activities have assumed that nuclear reactors are viable power sources for planetary surface activities. The use of the SP-100 technology for these applications is explicit in Case Study 3, and implicit in Case Study 4. However, the SP-100 program in its current form as a space-based reactor does not enable surface power for either case study. Studies need to be performed to fully conceptualize these nuclear power systems for planetary surface applications. Also, the output would have to be extended to the multi-megawatt range for the NEP applications envisioned for Case Study 4.

Preliminary assessments demonstrated that the application of Nuclear Thermal Rockets to the case study scenarios resulted in mass savings in LEO comparable to the use of aerobraking technology. The feasibility of the NTR concept was proven with experimental prototype NTR engine test-firing in the late-1960s as part of the NERVA program. Follow-on studies that build upon the

NERVA learning experience are warranted in future activities.

**Technology Demonstrations.** A major feature of the human exploration initiatives is that the eventual scenario or mission proposed to be flown will require the use of several new technologies. The groundrules for the preliminary assessments provide a certain latitude in assuming what technologies will be available. (Although forecasting technology development is a complex problem, it is certainly appropriate at this stage of the analysis.) However, one related issue is that major ground and/or flight demonstrations will be required for certain technologies, such as aerobraking, cryogenic fuel handling, closed-loop life support systems, fractional-gravity spacecraft prototypes, exploration vehicles (such as the Phobos Excursion Vehicle), nuclear power systems, and Ku-band telecommunications. These demonstration projects are long-lead-time issues and must be resolved prior to initiation of mission development. In order to preserve schedules 15-20 years in the future, these projects must be initiated immediately.

**Launch Year Sensitivity.** A fundamental aspect of missions to Mars is the sensitivity of the Earth-to-Mars sprint-class trajectory to launch opportunity; this sensitivity is illustrated in Figure 14. The IMLEO requirement can vary as much as 60 percent from opportunity to opportunity. These issues have profound effects on spacecraft design resiliency to meet launch delays. The implications to program cost to design a common interplanetary transport capable of capturing the mission in several consecutive opportunities are enormous. Therefore, optimum launch opportunities must be protected, or study activities must be initiated to develop options for decoupling the mass performance from launch year for the Earth-Mars mission legs. Potential solutions are to return to the use of conjunction-class trajectories, which are less sensitive to celestial geometry, or to use opposition-class trajectories, which have intermediate performance demands.

**Life Sciences.** Throughout the FY 1988 studies, the issues of life sciences, i.e., advanced medical care, long-duration exposure to zero gravity, long-term exposure to the natural space environment (radiation), life support, and space human factors, have not been specifically addressed. Although these issues have been acknowledged, they have been assumed to be solvable in the timeframe under consideration; however, they can have significant impacts. In fact, the answers to the life sciences issues will be mission design drivers. Crew size



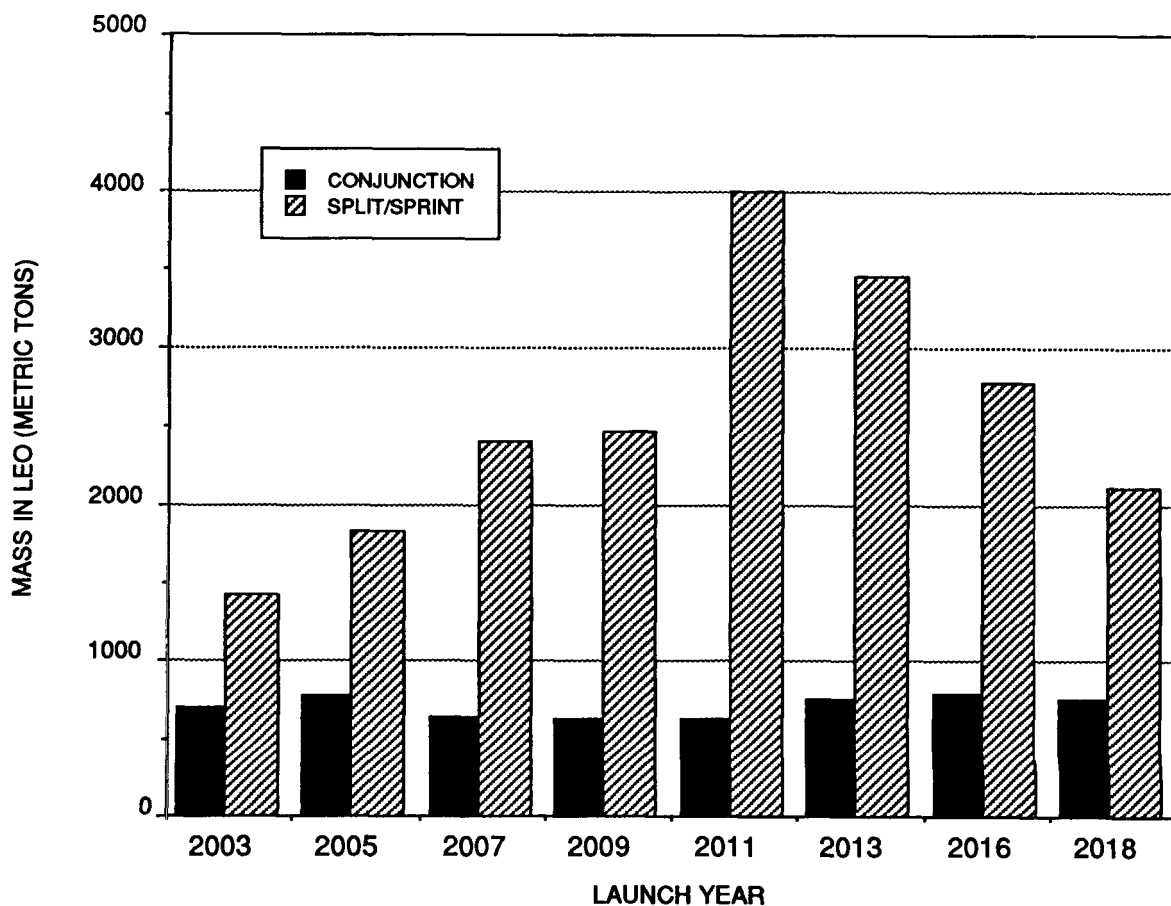


Figure 14. Initial LEO mass requirement sensitivity to launch year for human Mars missions

and adaptability to zero gravity (or the need for artificial gravity) and space human factors answers will drive spacecraft design. The resiliency of the human body to varying gravity loads and radiation hazards experienced throughout the mission will determine mission operations schedules and the exploration sequencing. Knowledge in all of the life sciences areas is critical.

**Phobos Operations.** The expedition to Phobos represents the first opportunity for human exploration in the Martian system without the associated complexity of landing upon Mars. However, Phobos possesses a unique set of environmental characteristics that make mission planning for human exploration of this moon extremely challenging. First, due to the low gravity conditions, the ability of humans to remain on the surface is a major issue. Related to maintaining surface contact to create a stable work platform is the issue of surface mobility for the human explorers. A third area requiring more detailed study is the issue of dust particle contamination as a result of Phobos's surface conditions in combination with the low surface gravity.

**Science Objectives.** The science objectives of the human

exploration missions were synthesized in FY 1988 and require more detailed definition than currently exists. The scientific community at large needs to be involved in order to provide guidance to the definition of the case studies. Once these objectives are more clearly defined and understood, they will be integrated into the case study mission scenarios for compatibility.

**Lunar Helium-3.** The use of lunar He-3 to provide nuclear fusion power on Earth could become the first truly extraterrestrial commercial venture with application and profit potential back on Earth. This is an area that demands a more detailed assessment in FY 1989. If the feasibility and practicality of mining lunar regolith to extract He-3 can be proven, this capability would have a far-reaching impact not only on human exploration missions but also on global commerce as well.

### Case Studies

**Human Expedition to Phobos.** The Phobos mission could be an excellent precursor to a manned Mars landing mission. The robotic exploration of Mars will provide improved knowledge of the Martian environment, and

the Phobos mission also will provide a unique opportunity to perform a systems checkout and verification of flight hardware and environment without the increased difficulty of a Mars landing. Therefore, future studies should consider the shaping parameters for a Phobos mission as a precursor for a manned Mars landing.

This document previously reported on the effects of new technologies, such as aerocapture and nuclear thermal rockets, in reducing the initial mass to LEO for the Phobos mission. These effects, and any possible consequences, should be explored in greater depth in subsequent studies. In addition, reducing the crew size to two, for example, further reduces the mass in LEO requirement, and subsequent ETO launches and space assembly operations. This crew of two concept was addressed at only a cursory level in FY 1988 and the potentially serious operational drawbacks to this approach must be addressed in greater detail in future analyses.

At the level of detail studied in FY 1988, it is not clear that the need for a LEO node has definitely been ruled out. If the requirement for no LEO node is maintained for the Phobos mission, then this is a key mission design study. Another area of future work that directly impacts the issue of a LEO node is the evaluation of the impact of artificial gravity/conjunction-class flight modes for the Phobos Expedition.

**Human Expeditions to Mars.** Of the four case studies analyzed in FY 1988, the Mars Expeditions have the most extensive requirements in terms of initial mass to LEO. All possibilities of reducing the mass requirements for the Mars Expeditions must be explored. One possibility is to evaluate the impact on Mars Expeditions of "scaled down" vehicles and systems. A second concept requiring further study is the use of the artificial-gravity/conjunction-class flight mode.

Two aspects of the Mars Expeditions that were not studied in detail this year were (1) the requirement for serial visits to the Martian moons on subsequent missions; and (2) the requirement for accessing Mars landing sites at latitudes beyond 45 degrees (north or south). The intent of having such capability is not only for expanded exploration purposes, but also because there exists a greater probability for near-surface water, a valuable component for life support and propellant production: both necessary ingredients for follow-on missions. The scenarios required to meet these objectives may have substantial impacts on mission performance and, consequently, initial mass in LEO. Therefore, study activities to resolve these two issues must be targeted for future planning.

**Lunar Observatory.** The Lunar Observatory case study has been defined and studied as an independent program. Viewed realistically, this is not likely to occur;

more probably, it would be carried out in combination with other lunar utilization programs (e.g., lunar oxygen production for Mars exploration). A formal study of a combined program is not proposed; however, the fundamental shaping parameters of such a combination should be understood so that we do not pursue options that may not be feasible. For example, permanent habitation facilities and continuous crew presence could have a major impact on the character of the Lunar Observatory.

The science facilities on the Moon will require the deployment of large, complex arrays. Although significant human interaction will be required for the assembly, deployment, operation, and servicing, the use of highly automated robotic assistance is a new technology that merits further detailed investigation.

**Lunar Outpost to Early Mars Evolution.** The technical understanding of Case Study 4 did not mature early enough in the FY 1988 study cycle to enable an in-depth analysis. Consequently, the mission design, element configuration definition, and overall case study synthesis were accomplished within the MASE function.

The analysis performed this year assumed the use of lunar-derived propellants, and, in the later years, of Phobos-derived propellants. The use of propellants derived from Mars itself was not included in the analysis and is an interesting option. Also, the analysis using the Electric Cargo Vehicle in this year's study activities will require updating next year, due to the in-depth definition activity performed in parallel by the Power and Propulsion Special Assessment Agents.

A third requirement for future study is to extend the case study time span beyond the first three Mars missions, in order to investigate the advantages of using Phobos propellants, and also the requirement for additional electric cargo vehicles.

### **Prerequisite Programs**

In most cases, the prerequisite program analyses demonstrate compatibility between the exploration mission support needs and the ability of the NASA Headquarters program offices to accommodate those needs. A few areas that remain outstanding and have need for focused attention in subsequent studies are:

1. ETO launch rate and capability versus on-orbit assembly options
2. Precursor missions interaction with the exploration mission programs; specifically, the development of planetary environments documents
3. Strategies to merge zero-gravity and artificial-gravity

Life Sciences Programs with exploration case study schedules

4. A better understanding of the technology needs of the Exploration Program as outlined above, coupled with a technology development program that is compatible with the Exploration Program milestones.
5. Further in-depth definition of exploration systems and elements to uncover latent advanced technology needs.

**ETO Transportation vs. On-Orbit Assembly Capabilities.** It is not obvious that the objective of no requirement for a LEO node has been satisfied by the Phobos mission design. To solve this problem requires a more focused, integrated study of the linkage between the ETO launch vehicles and the space transfer vehicles. Concepts to be investigated include: common stages, tethered concepts for fuel transfer, and very large launch vehicles.

**Precursor Missions.** The FY 1988 studies identified many areas and opportunities for interactions and mutual support between science missions and exploration missions (e.g., technology demonstration, atmospheric data, etc.). Future work for subsequent studies needs to be focused in two areas. One is to concentrate on further identification of exploration program needs and opportunities for mutual support. The other is to begin assessment of the value added to the exploration engineering design, mission safety, and system certification by alternative precursor strategies in order that optimum strategies can be planned.

The background information that facilitates this understanding can be found in the Prerequisite Requirements Document (PRD) and the planetary design environment document. Future work in the exploration case study area should be focused on developing an accurate set of requirements for the PRD. Regarding precursor support programs, attention should be focused on the planetary design environment document as well as potential precursor missions. The planetary design environment document should be produced in response to the PRD and should demonstrate how various precursor missions can improve knowledge of planetary environments.

**Life Sciences.** The Life Sciences Program for development and understanding of zero-gravity countermeasures and artificial-gravity techniques has become more mature during FY 1988. Since this issue is so fundamental to NASA's ability to execute any of these exploration missions, it is absolutely critical that an in-depth understanding of the integrated programs and program interactions be developed early. Research needs to focus on developing zero-gravity and artificial-gravity strategies (both Life Sciences Programs as well as vehicle design) that maximize the ability to respond to all potential outcomes of the Life Sciences Program and minimize impacts to vehicle and mission design.

**Technology.** The Technology support program needs for focused attention and subsequent studies were addressed earlier.

Any of these issues can be resolved through alternative case study strategies, accelerated technology programs, or interim, less optimum, solutions until technology readiness is achieved. Future work should assign special trade studies to investigate these issues and recommend solutions.

This Technical Summary uses a number of acronyms, abbreviations, and special terms. In order to facilitate the reader's comprehension of the text, a glossary is presented here.

### ACRONYMS AND ABBREVIATIONS

ETO	-	Earth-to-orbit
EVA	-	extravehicular activity
He-3	-	helium-3
IA	-	Integration Agent
IMLEO	-	Initial mass to low-Earth orbit
IVA	-	intravehicular activity
kg/kWj	-	propulsion system specific mass; power plant mass (kg) per kilowatt of jet power output
kW	-	kilowatt
kWe	-	kilowatts electric
kWt	-	kilowatts thermal
lbf	-	pound-force
LEO	-	low-Earth orbit
LH2	-	liquid hydrogen
LLO	-	low lunar orbit
LOX	-	liquid oxygen
LSS	-	Life Support System
L1	-	Earth-Moon libration point
MASE	-	Mission Analysis and System Engineering
MWe	-	megawatts electric
MWt	-	megawatts thermal
NASA	-	National Aeronautics and Space Administration
NEP	-	Nuclear Electric Propulsion
NERVA	-	Nuclear Engine for Rocket Vehicle Application
NLB	-	Nuclear Light Bulb
NTR	-	Nuclear Thermal Rocket
OEXP	-	Office of Exploration
PRD	-	Prerequisite Requirements Document
PV	-	photovoltaic
SAA	-	Special Integration Agent
SRGCR	-	Space radiator-cooled, open cycle gas core rockets
t	-	metric ton
TNIM	-	Telecommunications, Navigation, and Information Management

## DEFINITION OF TERMS

Aerobrake - Aerodynamic brake for use in planetary atmospheres.

Aerocapture - A technique of capturing a heliocentric spacecraft into a planetary orbit, using an aerobrake.

Beneficiation - Improving the chemical properties of an ore so that metal can be recovered.

Cislunar - Of or in the region of space between Earth and the Moon.

Cryogenic propellant - Propellant that must be stored at very low temperatures, e.g., liquid hydrogen and liquid oxygen.

Earth flyby injection maneuver - Interplanetary trajectory injection technique whereby the spacecraft makes a powered flyby gravity-assisted maneuver at Earth to reach critical injection energy.

Electric Cargo Vehicle - Unmanned cargo vehicle propelled by Nuclear Electric Propulsion System.

Exploration Requirements Document - Publication produced by the Office of Exploration that levies the overall exploration themes and objectives to initiate the FY 1988 studies activities.

Extraterrestrial propellant - Rocket fuel produced by the extraction of the appropriate constituents from a planetary body's environment.

Extravehicular activity - Any human activity outside protective shirt-sleeve environment and requiring a spacesuit.

Helium-3 - The isotope of helium with mass number 3, constituting approximately 1.3 parts per million of naturally occurring helium on Earth. In sufficient quantities, potential fuel for nuclear fusion reactors.

Heavy Lift Launch Vehicle - Earth-to-orbit vehicle with payload lift capability greater than 90 t to low-Earth orbit.

in situ - Latin expression meaning "in place" used to refer to extraterrestrial locations. One common usage is *in situ* propellant production, which is synonymous with extraterrestrial propellant production.

L1 - Libration point; critical point in Earth-Moon space where a body at rest would remain unless disturbed by an external force.

Launch stack - The completely assembled interplanetary transport vehicle plus all propulsion stages prior to the departure injection maneuver.

Leverage - Used to refer to any savings or benefits accrued through the incorporation of a particular option or capability.

Low-Earth orbit - A circular orbit about Earth with an altitude of approximately 300 to 500 km.

Low-Lunar orbit - A circular orbit about the Moon with an altitude of approximately 100 km.

Lunar day/night - Approximately 14 Earth days each. The Moon completes one revolution about Earth in approximately 28 days.

Magnetoplasmadynamics - The generation of electric current by shooting a beam of ionized gas through a magnetic field.

"Magnum" Heavy Lift Launch Vehicle - Earth-to-orbit vehicle with 200-250 metric ton capability to low-Earth orbit.

Mission Analysis and System Engineering - The Mission Analysis and System Engineering (MASE) is a Level II implementation function of the Office of Exploration. The MASE group will decompose the scenario requirements into collections of top-level, functional requirements that must be accomplished by the Integration Agents (IAs). The IAs will develop concepts that implement these requirements and furnish this information to MASE for integrated systems synthesis and total scenario option evaluation.

MASE will also develop scenario-dependent study issues for the Special Assessment Agents (SAAs) and, as results are available from the SAAs, will assess total scenario impacts.

National Space Policy and Exploration Guidelines -

- The policy specifies that in conjunction with other agencies: NASA will continue the lead role within the Federal Government for advancing space science, exploration, and appropriate applications through the conduct of activities for research, technology, development, and related operations.
- Space Science - NASA, with the collaboration of other appropriate agencies, will conduct a balanced program to support scientific research, exploration, and experimentation to expand understanding of: (1) astrophysical phenomena and the origin and evolution of the universe; (2) the Earth, its environment and its dynamic relationship with the Sun; (3) the origin and evolution of the solar system; (4) fundamental physical, chemical, and biological processes; (5) the effects of the space environment on human beings; and (6) the factors governing the origin and spread of life in the universe.
- Space Exploration - In order to investigate phenomena and objects both within and beyond the solar system, the policy states that NASA will conduct a balanced program of manned and unmanned exploration.
  - Human Exploration - To implement the long-range goal of expanding human presence and activity beyond Earth orbit into the solar system, the policy directs NASA to begin the systematic development of technologies necessary to enable and support a range of future manned missions. This technology program (Pathfinder) will be oriented toward a Presidential decision on a focused program of manned exploration of the solar system.
  - Unmanned Exploration - The policy further directs NASA to continue to pursue a program of unmanned exploration where such exploration can most efficiently and effectively satisfy national space objectives by, among other things, achieving scientific objectives where human presence is undesirable or unnecessary, exploring realms where the risks or costs of life support are unacceptable, and providing data vital to support future manned missions.

Nuclear electric propulsion - Low-thrust electric propulsion, with electric power provided by nuclear reactor.

Nuclear light bulb - A type of closed-cycle gas core nuclear thermal rocket.

Nuclear Thermal Rocket - A space propulsion concept in which the heat from a nuclear fission reactor is used to raise the temperature of the propellant, which is then expanded through a nozzle to provide thrust. Two types of nuclear thermal rockets have been studied: gas core and solid core.

Office of Exploration Case Studies - The OEXP case studies are specific mission scenarios that execute the exploration goals according to the objective content of the themes and strategies. Each case study may contain several optional implementation approaches. The case studies will be initiative-specific; each case study and its optional implementation approaches will address a single strategy. The four case studies analyzed in FY 1988 are:

1. Human Expedition to Phobos
2. Human Expeditions to Mars
3. Lunar Observatory
4. Lunar Outpost to Early Mars Evolution

Office of Exploration Strategies - The OEXP strategies present particular opportunities for meeting defined OEXP themes. To organize and systematically examine a full range of options for human exploration and development of the Moon and Mars, three strategies were identified for study in FY 1988: 1) Expeditions, 2) Science Outpost, and 3) Evolutionary Expansion.

Office of Exploration Themes - The OEXP themes describe basic, upper-level objectives for space exploration: national pride, advancement of scientific knowledge, etc. These themes provide a synthesis and a translation of the National Space Policy goals into a set of objectives that are compatible with the charter of the OEXP. These themes will be used to guide the generation of case study development requirements. The OEXP will produce and control the themes.

Photovoltaic - Capable of generating a voltage as a result of exposure to visible or other radiation.

Precursors Requirement - Science, technology, or operational data needed as critical path information to enable selection of specific habitation site location, location/objectives of specific user surface activities, systems design options, or specific operational approaches to human exploration. Precursor data are usually obtained via robotic, highly automated missions.

Prerequisite Requirements - A technical space system performance capability necessary for the execution of one or more exploration initiatives or scenarios. Prerequisite requirements are part of the exploration study and define case study-specific technology, space system, and operational support needs at a level of detail sufficient to enable the receiving program organization to proceed with its implementation strategy: either the development of new hardware elements, the modification of previously defined or existing hardware elements, or the use of existing hardware elements in support of the multiprogram initiative implementation effort.

Prerequisite Requirements Document - Publication produced by the OEXP levying the required supporting precursor activities upon the other NASA Headquarters codes.

Propellant Tank Farm - Collection of propellant tanks for on-orbit fueling of interplanetary spacecraft.

Shuttle-C - Space Shuttle derivative proposed unmanned cargo vehicle.

SP-100 - 100-kWe-class of space power systems.

Special assessment agents - Directors of independent studies targeted toward the identification of high leverage technologies, systems, or operational techniques. SAAs are truly independent and are not used as systems or subsystem definition agents for system designers.

Specific impulse - A performance parameter of a rocket engine, expressed in seconds, equal to the thrust in pounds divided by the weight flow rate in pounds per second.

Stirling engine - An engine in which work is performed by the expansion of a gas at high temperature; heat for the expansion is supplied through the wall of the piston cylinder.

Strongback - Structural member that provides rigidity in bending and torsion.

Study Requirements Document - Publication produced by MASE levying the case study ground rules upon the integration and special assessment agents.

Teleoperator - A general-purpose, remotely controlled, cybernetic, dexterous person-machine system.

Telerobotic - Referring to automated systems operated remotely.

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16. Abstract The Office of Exploration (OEXP) at NASA Headquarters has been tasked with defining and recommending alternatives for an early 1990's national decision on a focused program of human exploration of the solar system. The Mission Analysis and System Engineering (MASE) group, which is managed by the Exploration Studies Office at the Lyndon B. Johnson Space Center, is responsible for coordinating the technical studies necessary for accomplishing such a task. This technical report, produced by the MASE, describes the process that has been developed in a "case study" approach. The four case studies that were developed in FY 1988 include: <ol style="list-style-type: none"> <li>1. Human Expedition to Phobos</li> <li>2. Human Expeditions to Mars</li> <li>3. Lunar Observatory</li> <li>4. Lunar Outpost to Early Mars Evolution</li> </ol> <p>The final outcome of this effort is a set of programmatic and technical conclusions and recommendations for the following year's work.</p>					
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